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THE POTENTIAL EFFECTS OF GLOBAL CLIMATE CHANGE ON THE UNITED STATES

DRAFT

REPORT TO CONGRESS

Volume 1: Regional Studies

United States Environmental Protection Agency

Office of Policy, Planning, and Evaluation

Office of Research and Development

October, 1988

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Volume 1: Regional Studies

Editors: Joel B. Smith and Dennis A. Tirpak

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DISCLAIMER

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Chapter 3:	Methodology	Joel B. Smith
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Chapter 5:	Great Lakes	Joel B. Smith
Chapter 6:	Southeast	James G. Titus
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Chapter 18:	Research Needs	Anthony Janetos
Chapter 19:	Policy	James G. Titus

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DRAFT

CHAPTER 1

INTRODUCTION

Since the beginning of the Industrial Revolution, emissions of greenhouse gases have increased. Fossil fuel burning, which releases CO_2, CO, N_2O, and other pollutants, has expanded many times over. Changes in agriculture have led to increased emissions of CH_4 and N_2O. Population growth has contributed to deforestation in many areas of the globe, which in turn has affected the global carbon cycle. Atmospheric concentrations of tropospheric ozone and CFCs have also increased, primarily due to industrial activity.

Scientists studying the effect of increasing concentrations of greenhouse gases have tried to predict how quickly and to what extent atmospheric temperature may rise. For analytic convenience, the convention has been to examine the implications of a CO_2 doubling. In 1979, the National Academy of Sciences concluded that such a doubling would lead to an increase of 1.5 to 4.5°C in global air temperatures. Since then, other researchers have examined the increase in all greenhouse gases and have concluded that greenhouse gas increase equivalent to CO_2 doubling will occur as early as the 2030s, with commensurate global warming lagging by several decades.

The earth's atmosphere has undergone many cycles of warming and cooling in the past. Paleoclimatologists have estimated that at the glacial maximum of the last ice age, which was about 18,000 years ago, the earth was approximately 5°C cooler than at present. This is generally attributed to changes in orbital characteristics combined with lower trace gas concentrations and different climate feedbacks. Two things are different about current greenhouse warming. First, it will raise temperatures higher than the planet has experienced in the last 100,000 years. Second, past climate changes of comparable magnitude have generally occurred over tens of thousands of years. The greenhouse effect is expected to raise atmospheric temperatures several degrees in less than a century.

CONGRESSIONAL REQUEST FOR REPORTS

The significant implications of the greenhouse effect have been the subject of discussion within the scientific community for the past three decades. In recent years members of the Congress have held hearings and began to explain the implications for public policy. This interest was accentuated during a series of hearings held in June 1986 by the Subcommittee on Pollution of the Senate Environment and Public Works Committee. Following the hearings, members of the Senate Environment and Public Works

Committee sent a formal request to the EPA Administrator, asking the Agency to undertake two studies on climate change due to the greenhouse effect.

> One of the studies we are requesting should examine the potential health and environmental effects of climate change. This study should include, but not be limited to the potential impacts on agriculture, forests, wetlands, human health, rivers, lakes, and estuaries, as well as other ecosystems and societal impacts. This study should be designed to include original analyses, to identify and fill in where important research gaps exist, and to solicit the opinions of knowledgeable people throughout the country through a process of public hearings and meetings.

The Congress also requested that EPA prepare a study on policy options to stabilize current levels of atmospheric greenhouse gas concentrations. This study analyzes policy options for limiting gas concentrations including energy efficiency, alternative technologies, reforestation options, CFC reductions, and other options for limiting CH_4 and N_2O. Congress requested the studies in the Fiscal Year 1987 Continuing Resolution.

GOALS OF THIS REPORT

This report builds on the past contributions of many scientists throughout the world. Most notably, the reports by the National Academy of Sciences (1979, 1983, 1987), the World Meterological Organization, United Nations Environment Programme, and the International Council of Scientific Unions (1985), Scope 29 (1986), Department of Energy (1985). It is an attempt to identify some of the sensitivities, direction and magnitude, linkages, regional differences, national impacts, policy implications, and uncertainties among the effects of global climate warming, but it is not a prediction. We hope it will provide useful information to climate modelers and effects researchers. We also hope that officials, at all levels of government will be encouraged to examine the implications of climate change on long-term policies. Since this is the first study of this type, we expect that a great deal more research, analysis, and planning will be needed in the future. We do not pretend to have all the answers.

This report is intended to achieve the following goals of identifying:

Sensitivities

Since climate change on a regional level is uncertain, we cannot predict regional effects. However, we can identify the sensitivities of systems to climate change. Our goal is to use a variety of scenarios to determine what climatic variables are important in causing impacts and how sensitive systems are to changes in these variables.

Direction and Magnitude

Since the scenarios do not encompass all possible combinations of climate change due to increased greenhouse gases, the results do not represent the entire range of possible effects. Yet, the results from various scenarios help define the direction and magnitude of effects. First, we examine them to see if a direction of change (e.g. more water, lower crop yields) is evident. Second, we attempt to determine if the magnitude of change is significant. Yet, results outside the bounds of our results cannot be ruled out at this time.

Linkages

Individual environmental systems will not be affected by climate change in isolation. Water resources, for example, may be affected not only by changes in water supply, but also by changes in demand for water for such purposes as irrigation. Wildlife may be directly affected by changes in climate and indirectly by changes in habitat. This report attempts to identify linkages among effects, quantitatively, where possible, and qualitatively elsewhere.

Regional Differences

Effects were examined in several regions to broaden the analysis and to allow for comparison of effects on similar systems in different regions. We do not attempt to identify "winners and losers" since all regions are likely to change. The effects are simply likely to occur in different sectors and at different rates.

National Impacts

While regional case studies are the major method used in this report, several issues have been analyzed on national scales. National analyses can build on regional studies to provide more comprehensive information on the sensitivities of systems to climate change. In some cases, national analyses gives us some insights into the total cost to the United States over the next 50 to 100 years.

Policy Implications

In their current decisions on the use of natural resources and related systems, States, municipalities, industries, and businesses are assuming that climate will not change. An examination of the sensitivities of systems to climate change may indicate that they should reconsider some of their long-term decisions. This report discusses some policy implications of climate change, but it does lay out a prescription policy agenda.

Uncertainties

There are many uncertainties about the rate of warming and specific changes in regional weather patterns. There are also uncertainties about how ecological and other systems will be affected by climate change. These uncertainties are reflected in the models used to estimate climate change and impacts. This report attempts to clearly state these limitations.

Guidance for Research

This effects analysis should provide climate modelers with information about how general circulation models could be improved. It should also help define research needs for future analysis of the potential impacts of climate change.

Fundamentally, these goals center on the identification of important issues and state-of-the-science investigations in each environmental system. Because each component of science and policy development is at an early stage, the goals of the report are to develop insights and estimates of the ranges of possible future effects and to use that information for identifying where the policies and research programs of EPA and other agencies should be reexamined.

STRUCTURE OF THE ANALYSIS

Key Systems

This report focuses on several systems that may be particularly affected by climate change.

Sea Level Rise
Water Resources
Agriculture

Forests
Biodiversity and Wildlife
Energy Demand
Air Pollution
Health

Regional Case Studies

Analysis of the regional impacts of climate change on various resources help display the diversity of possible effects of climate change across the United States and make the possible effects of global climatic change easier to understand. Analysis of regional impacts also makes it easier to identify and analyze the interrelationship of effects and possible responses. For example, rising sea level and reduced river flow would have combined impacts on estuarine salinity. Changes in agriculture could lead to increased demand for irrigation, further reducing available water supplies. Furthermore, the identification of combined effects on a regional scale aids in the analysis of potential adaptation strategies.

Four regional case studies were selected: the Southeast, the Great Lakes, California, and the southern Great Plains. These regions were picked for several reasons. Each of these regions is important for economics, social, and environmental reasons, and each offers some unique current characteristics that makes it an interesting example of the range of possible environmental issues that will most likely need to be considered. The Southeast depends heavily on forestry and agriculture, and has extensive and fragile wetlands and coastal ecosystems. The Great Lakes are the dominant natural resource in their region, supplying freshwater, fishery resources, and a pathway for shipping and transportation, and provide a natural laboratory for environmental issues that affect both the United States and Canada. California already must manage its water supplies carefully, and its agricultural industry provides many crops for the United States, a large share of the international market, and is among the most productive agricultural regions in the world. The Great Plains is one of the largest producers of grain crops in the world. Although these regions are diverse, they do not encompass the entire range of regional differences in the United States. The analysis of effects in these regions does not cover all potential impacts in the United States.

National Studies

The effects on a number of systems were quantitatively analyzed on a national scale. National agricultural markets were analyzed with respect to their sensitivities to changes in yield derived from our agricultural models. Options for adapting to a sea level rise were examined on a national scale, as were the possibilities of health impacts. Forestry, water management, air quality, and biodiversity issues were explored by analyzing the results of several of the regional case studies with a broader perspective. In each case, the national-level analyses provide an additional level of qualitative integration that a purely regional analysis could not. The structure of the regional and national studies is displayed in Figure 1-1.

ANALYTIC APPROACHES

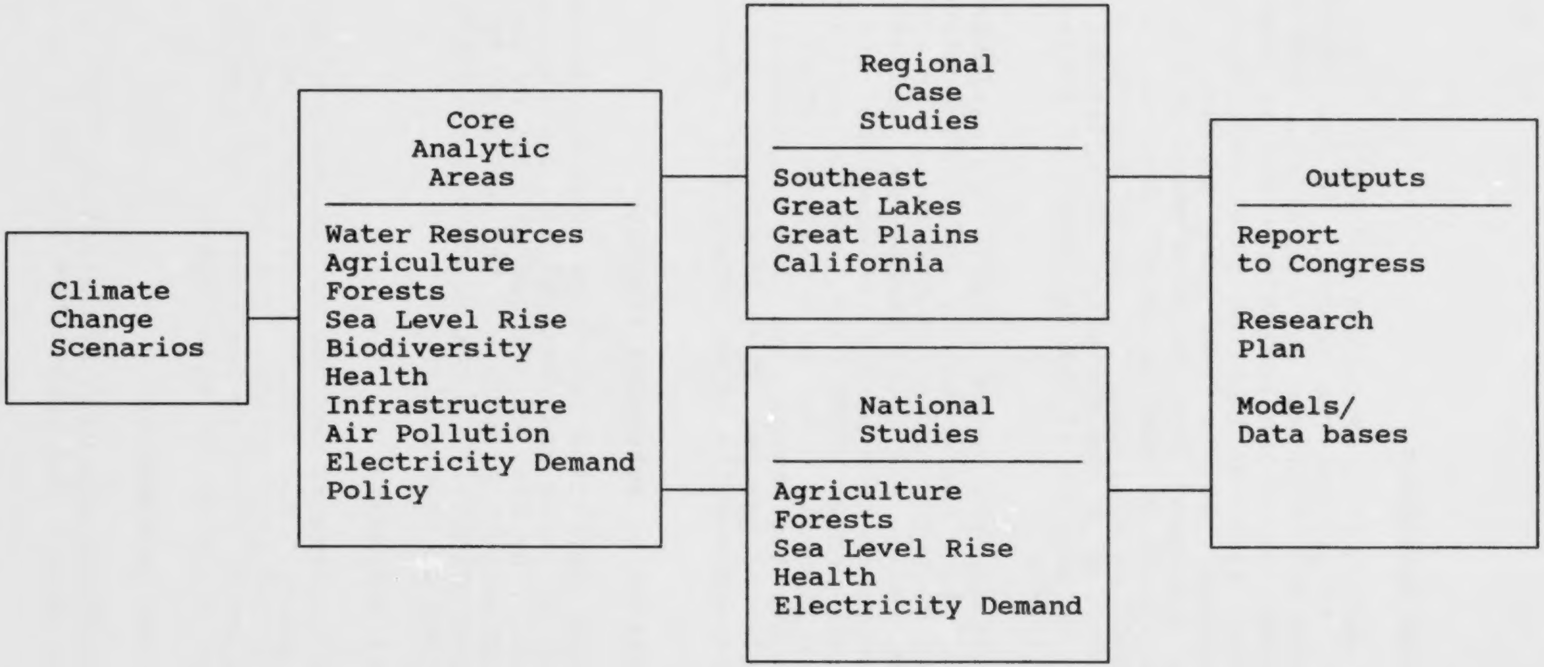
The climate scenarios we used were based on outputs from General Circulation Models (see Chapter 3). Where possible, we tried to obtain quantitative estimates of effects. However, the development of quantitative estimates was constrained by the availability of well-documented models that included some interaction of the particular effect in question and climatic variability. We obtained information on sensitivities by reviewing the literature and by gathering expert judgement. The approach of using existing models, all of which were originally constructed for other purposes, makes the interpretation of results instructive, but somewhat limited with respect to the full range of climatically relevant questions that could be asked.

PROCESS

We used a seven-stage process to define the scope of this report, select the projects, write the chapters, and review the results.

Step 1: Initial Scoping of the Report

This stage immediately followed the request from the Senate Environment and Public Works Committee. We agreed on using the regional case study approach and the four regions to be investigated, and on using climatic scenarios. We also decided not to attempt to analyze environmental effects outside of the United States in this report. Our rationale for thisdecision was based on available time, funds, and the lack of suitable models that would be immediately accessible to us.


Climate
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Scenarios
Core
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Areas
Water Resources
Agriculture
Forests
Sea Level Rise
Biodiversity
Health
Infrastructure
Air Pollution
Electricity Demand
Policy
Regional
Case
Studies
Southeast
Great Lakes
Great Plains
California
National
Studies
Agriculture
Forests
Sea Level Rise
Health
Electricity Demand
Outputs
Report
to Congress
Research
Plan
Models/
Data bases

Figure 1-1. Elements of Effects Report

Step 2: Preparatory Workshops

We held two workshops in February and April, 1987 in Boulder, Colorado, to prepare the report. In the February workshop, sponsored and organized by the National Center for atmospheric Research, general circulation modelers convened to discuss some of the problems inherent in attempting to understand the regional results from global models. several major topics were discussed from the standpoint of how the results from GCMs should be used in impact studies. A list of variables that would be available for use by effects researchers was produced at the end of the workshop. In addition, several potential studies on aspects of the frequency of extreme weather events were identified.

The April workshop was organized with the assistance of the University of Colorado. Approximately one hundred scientists explored the major climate change related issues in agriculture, forest effects, hydrology and water management, and sea-level rise. Working groups in each discipline discussed the potential impacts that climate change might have, and the most important uncertainties to explore in order to arrive at better predictions. The working groups were then rearranged into geographically oriented groups. They identified a series of studies that would address the major scientific issues in each region.

Step 3: Identification of Potential Projects

From the lists identified in the two Boulder workshops, and additional studies on urban and regional air quality subsequently identified internally by EPA, we arrived at list of investigators from whom we would solicit proposals. The decision to solicit proposals was based primarily on the potential coverage of environmental issues in each region.

Step 4: Reviews of Proposals

At least one intramural and two extramural reviewers examined each proposal. All comments were responded to and proposals modified and appropriate. EPA used a combination of cooperative agreements, existing contracts, and interagency agreements to fund projects for this report.

Step 5: Planning and Integration

All the researchers met with EPA staff in October 1987 to discuss scenarios, goals, and approaches for the studies.

Researchers discussed integration of projects within regions as well as the commonality of approaches within disciplines.

Step 6: Preliminary Project Review

In April 1988, EPA assembled panels of scientists to provide a preliminary review of most of the agriculture, forestry, and hydrology projects. The principal investigators of the appropriate projects were asked to present their work orally and in written drafts. EPA project managers used the comments from the review panels to make mid-course corrections in the conduct of a few projects, and as a guide to interpreting the results of individual projects.

Step 7: Project and Report Peer Review

At least two to three reviewers examined the final reports from all principal investigators before the EPA project managers accepted them. During this time, EPA staff on the report project team wrote the overviews that are reflected in this final report. In October 1988, a special subcommittee of EPA's Science Advisory Board was convened and asked to review the entire Environmental Effects Report. Following the SAB's written review, the EPA project team responded to comments and produced the final version of the Environmental Effects Report. The draft of the report was simultaneously sent to other Federal agencies for review and comment, and these comments were also taken into account in the final version.

STRUCTURE OF THIS REPORT

This report is divided into several sections. Section I consists of Chapter II on trends in emissions of greenhouse gases and potential impacts on climate; and Chapter III on the choice of scenarios and effects modelling. Section II contains results from the regional case studies, with each chapter devoted to different regions. Each regional chapter describes the climate sensitive stems in the region, reviews previous studies on impacts of climate change on the region, describes the structure of regional studies for the report, discusses regional climate change scenarios, reviews the design, results, and limitations of the studies and discusses the broader socio-economic and policy implications of climate change for the region. The regional chapters include relevant regional results from national studies. In Section III, the results of national analyses are presented. Each chapter covers a different system. They include an overview of relevant regional studies and presentation of results from national analyses. Each chapter discusses the current state of issue, reviews previous literature on climate change and the issue, discusses studies used for this report, presents national results from regional and national studies, and discusses broader socio-economic and policy implications. The design and limitations for each study are presented only once - in a regional chapter if it is a regional study or in a national chapter if it is a national study. Not all regionally relevant results are presented in the appropriate regional chapters. Results for health and livestock are presented only in the Health and Agriculture chapters. Section IV includes conclusion chapters. It begins with an overview of studies on climate variability. Chapter XVIII discusses where future research on climate change effects should go and Chapter XIX discusses policy implication and recommendations.

This report is meant as an overview of the individual studies. Those studies are printed in appendix volumes. In the overview, the studies are referenced by the author's name or names in parentheses. Previous published work is reference by the author's name and year of publication.

RELATIONSHIP TO CURRENT NATIONAL AND INTERNATIONAL ACTIVITIES

National Research and Policy Activities

The Global Climate Protection Act of 1987 requested EPA to develop a national policy on global climate change and to prepare an assessment of scientific information. The very scope of this issue suggests that this request can only be fulfilled in cooperation with other federal agencies, hence, EPA is working with these agencies to formulate a process to fullfill this request. The scientific assessment will be conducted in coordination with NASA, NOAA, NSF, and other agencies. To the extent possible, this scientific assessment will also be developed on an international basis and should be available in 1990.

The development of a national policy will be coordinated with the Department of Energy and other natural resource departments. The goal will be to build on this report and others under development by Federal agencies to identify the adoptive policies and other measures that may be appropriate to deal with this issue. An interim report on a national policy is scheduled for development by the end of 1989. The nature of this issue suggests that a continuous review of domestic policy will be required for many years into the future.

International Activities

In 1987, the United Nations Environment Programme (UNEP) and the World Meterological Organization (WMO) were asked by member governments to establish an Intergovernmental Panel on Climate Change (IPCC) for the specific purpose of reviewing the scientific information and potential response strategies. The World Meterological Programme has primary responsibility for the World Climate Research Programme and the United Nations Environment Programme has responsibility for the World Climate Impacts Programme. The UNEP was the primary international agency responsible for negotiations leading up to the Montreal Protocol to Protect the Ozone Layer. As this report is being developed, the agenda for the IPCC has not yet been agreed upon by participating governments. The first meeting is scheduled for November 1988. Nevertheless, it is expected that the IPCC will be the primary forum for multilateral discussions between governments on this issue.

Other governments and international agencies are also examining this issue. Conferences are currently planned in 1989 by Italy, Canada, and the Netherlands. The United States has bilateral activities with the Soviet Union and China. The Organization for Economic Cooperation and Development (OECD) and the International Energy Agency are examining their potential contributions.

CHAPTER 2

GLOBAL CLIMATE CHANGE

The last two decades have witnessed a substantial increase in interest in the greenhouse theory. Once the subject of purely scientific curiosity during the last half of the nineteen century (Tyndall, 1863), the greenhouse process is now generally recognized as essential to the existence of life on earth in its current forms. Water vapor and carbon dioxide as primary trace gases were the first to receive attention. The scientific community developed a hierarchy of models with increasingly complex representations of the atmosphere, oceans, and terrestrial biosphere to represent the earth's climate and understand the greenhouse effect.

During the last decade, several developments have broadened the focus of scientific investigations on this global warming. The first was the finding that other trace gases--e.g., the chlorofluorocarbons (CFCs), methane ($_CH_4$), and nitrous oxide (N_2O)--could have a greater temperature effect on a molecule-per-molecule basis than CO_2. The second was the increasing recognition that these other trace gases could substantially alter the chemical composition and temperature of the atmosphere. Stratospheric ozone changes recently became the subject of intense laboratory and field experiments as scientists have struggled to understand the Antarctic ozone. Finally, it was recognized that the growth rates of these other trace gases are such that their combined growth could result in the equivalent doubling of CO_2 by approximately 2030 -- a time much sooner than previously assumed.

These discoveries lead the climate research community to deal with a series of challenges with a new urgency, including the chemistry of the stratosphere and the troposphere, the radiation balance of the planet, the importance of climate feedback mechanisms, and the role of the oceans in global climate. In addition, a variety of studies have been assembled to review current scientific information on the greenhouse effect, including reports by the National Academy of Sciences (NAS, 1979, 1983, 1987) and the World Meterological Organization (WMO, 1986a; 1986b). All these studies support the hypothesis that increasing concentrations of trace gases will lead to a global warming.

This chapter reviews and synthesizes the results of these prior efforts. Together, these sections are intended to provide a broad overview of the major issues affecting our knowledge of the greenhouse effect. The EPA report (EPA, 1989) on policy options for stabilizing the atmosophere provides a more detailed treatment of the factors affecting the earth's climate.

GREENHOUSE THEORY

The greenhouse effect may be described as the process by cwhich the biosphere balances the earth's energy budget. The main components of this process are incoming radiation from the sun, some of which is reflected back to space, and the outgoing longwave (infrared) radiation at the top of the atmosphere (Figure 2-1). The trace gases, mainly composed of CO_2, and water vapor, allow solar radiation to pass through the atmosphere to the earth's surface. Infrared radiation from the earth's surface is partly trapped by the greenhouse gases which are mainly CO_2 and water vapor. Scientists estimate that without the pretense of greenhouse gases, the earth would be approximately 58°C colder. The relative transparency of the gases to solar radiation and the trapping of infrared radiation is commonly referred to as the greenhouse effect.

When concentrations of radiatively important greenhouse gases increase, less longwave infrared passes back to space, and the global energy budget shown in Figure 2-1 becomes imbalanced. That is, less energy leaves the atmosphere than enters it. To maintain a balance with incoming solar radiation,--i.e., a net radiative flux at the top of the atmosphere equal to zero,--the lower part of the atmosphere (the troposphere) and the surface warm, increasing the emission of infrared radiation into space, until a new balance is achieved. Hence, as more greenhouse gases increase in the atmosphere, more infrared radiation is trapped, and the greater greenhouse effect. One very important factor in this greenhouse process is the altitude of the greenhouse gases. In general, gases absorbing solar radiation in the lower troposphere tend to warm the earth's surface, while gases absorbing radiation in the stratosphere tend to cool it.

THE ROLE OF TRACE GASES

It is now recognized emissions of many greenhouse gases are increasing and that these gases influence the chemistry of the stratosphere and troposphere in many ways. (A comprehensive discussion of greenhouse gases can be found in WMO, 1985; Ramanathan, 1985; Wang et al., 1986; and EPA, 1988). The radiatively important gases include water vapor, carbon dioxide,

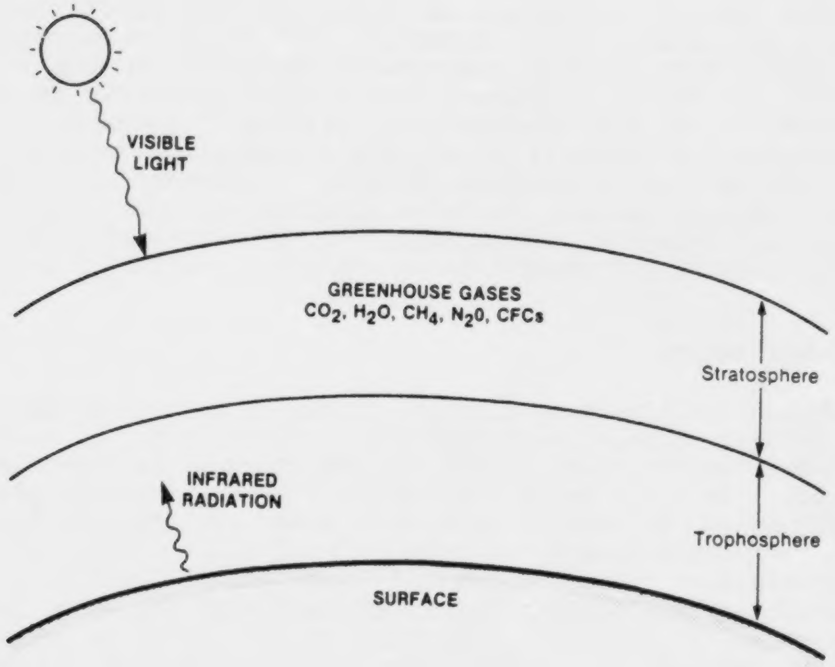
VISIBLE LIGHT
GREENHOUSE GASES
CO_2, H_2O, CH_4, N_20, CFCs
Stratosphere
INFRARED RADIATION
Trophosphere
SURFACE

Figure 2-1. Global energy balance and the greenhouse effect.

Source: World Meteorological Organization (1985).

methane, chlorofluorocarbons, nitrous oxide, and tropospheric ozone. Other gases that are important because of their direct radiative effect or because of their role in the chemistry of the atmosphere include chlorocarbons, hydrocarbons, aldehydes, fluorinated and brominated species, carbon monoxide, nitrogen oxides, and compounds of sulfur.

The lifetimes, dominant sources, and sinks of greenhouse gases are shown in Table 2-1. Once emitted into the atmosphere, these greenhouse gases will be present for more than 100 years. In addition, they absorb radiation in parts of the electromagnetic spectrum that generally allow longwave radiation to escape into space. The gases have strong absorptive features in the 7-13 M spectral band, as shown in Figure 2-2. This spectral region is often referred to as the atmospheric "window," because in this region the atmosphere there is relatively transparent to radiation. Pollutants with strong absorptive features, however, can be very effective greenhouse gases, because they dirty the atmospheric window and block longwave radiation. The relative effectiveness of fifteen different greenhouse gases is shown in Table 2-2.

TRENDS IN TRACE GASES

Information on the composition of the atmosphere generally comes from either direct measurements, mostly made in the last several decades, or by measurement of gas trapped in Greenland or Antarctic ice. In some cases, attempts to measure old gas have even been directed at exotic sources, such as ancient-Egyptian tombs. For easy comparison, we have placed the records of three important greenhouse gases alongside each other in Figure 2-3. While not matching perfectly, the instrument and ice core records generally appear to overlap. In some cases, such as with CH_4, concentrations appear to mirror the general growth in global populations, while in other cases, such as with CO_2, concentrations appear to follow the direct growth in industrial activities. The following is a brief summary of observed trends.

Carbon Dioxide (CO_2) - The most reliable recent measurements of CO_2 were initiated by Keeling in 1958, when concentrations on Mauna Loa, Hawaii, were found to be 315 ppm. This compares to a number of ice core studies that generally place the preindustrial concentrations in the range of 270-290 ppm. The mean growth of CO_2 for the period 1850-1958 was about 4ppm/decade, while the growth in recent

Table 2-1. Estimates of the Abundance of Trace Chemicals in the Global Atmosphere of Years 1980 and 2030.
Source: Ramanathan, Cicerone, Singh and Hiehl (1985)

Chemical Group	Chemical Formula	Dominant Source*	Dominant Sink*	Estimated Average Residence Time (τj)	Year 1980 Global Average Mixing Ratio (ppb)+	Year 2030 probable global average concentration		Remarks (also see text for details)
						Probable Value	Probable Value	
Carbon Dioxide	CO_2	N.A	O	2	$339x10^3$	$450x10_3$	--	Based on a 2.4% per year increase in anthropogenic CO_2 release rates over the next 50 years
Nitrogen Compounds	N_2O	N.A	S(UV)	120	300	375	350 - 450	Combustion and fertilizer sources
	NH_3	N.A	T	0.01	<1	--	--	Concentration variable and poorly characterized
	$(NO+NO_2)$	N.A	T(OH)	0.001	0.05	0.05	0.05 - 0.1	Concentration variable and poorly characterized
Sulfur Compounds	CSO	N.A	T(O.OH)?	I(?)	0.52	0.52	--	Sources and sinks largely unknown
	CS_2	N.A	T	I(?)	<0.005	<0.005	--	Sources uncharacterized
	SO_2	A(?)	T(OH)	0.001	0.1	0.1	0.1 - 0.2	Given the short lifetime the global presence of SO_2 is unexplained
	H_2S	N	T(OH)	0.001	<0.05	<0.5	--	
Fully Fluorinated Species	CF_4(F14)	A	I	>500	0.07	0.24	0.2 - 0.31	Aluminum industry a major source
	C_2F_6(F116)	A	I	>500	0.004	0.02	0.01 - 0.04	Aluminum industry a major source
	SF_6	A	I	>500	0.001	0.003	0.002- 0.05	
Chlorofluorocarbons	$CClF_3$(F13)	A	S(UV).I	400	0.007	0.06	0.04 - 0.1	All chlorofluorocarbons are of exclusive man-made origin. A number of regulatory actions are pending. The nature of regulatory actions are pending. The nature of regulations and their effectiveness would greatly affect the growth of these chemicals over the next 50 years
	CCl_2F_2(F12)	A	S(UV)	110	0.28	1.8	0.9 - 3.5	
	$CHClF_2$(F22)	A	T(OH)	20	0.06	0.9	0.4 - 1.9	
	CCl_3F(F11)	A	S(UV)	65	0.18	1.1	0.5 - 2.0	
	CF_3CF_2Cl(F115)	A	S(UV)	380	0.005	0.04	0.02 - 0.1	
	$CClF_2CClF_2$(F114)	A	S(UV)	180	0.015	0.14	0.06 - 0.3	
	CCl_2FCClF_2(F113)	A	S(UV)	90	0.025	0.17	0.08 - 0.3	
Chlorocarbons	CH_3Cl	N(O)	T(OH)	1.5	0.6	0.6	0.6 - 0.7	Dominant natural chlorine carrier of oceanic origin
	CH_2Cl_2	A	T(OH)	0.6	0.03	0.2	0.1 - 0.3	A popular reactive but non-toxic solvent
	$CHCl_3$	A	T(OH)	0.6	0.01	0.03	0.02 - 0.1	Used for manufacture of F22; many secondary sources also exist
	CCl_4	A	S(UH)	25-50	0.13	0.3	0.2 - 0.4	Used in manufacture of fluorocarbons; many other applications as well
	CH_2ClCH_2Cl	A	T(OH)	0.4	0.03	0.1	0.06 - 0.3	A major chemical intermediate (global production=10 tg/yr); possibly toxic

Table 2-1. Estimates of the Abundance of Trace Chemicals in the Global Atmosphere of Years 1980 and 2030.
Source: Ramanathan, Cicerone, Singh and Hiehl (1985) (continued)

Chemical Group	Chemical Formula	Dominant Source*	Dominant Sink*	Estimated Average Residence Time (τj)	Year 1980 Global Average Mixing Ratio (ppb)+	Year 2030 probable global average concentration Probable Value	 Probable Value	Remarks (also see text for details)
	CH_3CCl_3	A	T(OH)	8.0	0.14	1.5	0.7 - 3.7	Non-toxic, largely uncontrolled degreasing solvent
	C_2HCl_3	A	T(OH)	0.02	0.005	0.01	0.005- 0.02	Possibly toxic, declining markets because of substitution to CH_3CCl_3
	C_2Cl_4	A	T(OH)	0.5	0.3	0.07	0.03 - 0.2	Possibly toxic; moderate growth due to substitution to CH_3CCl_3
Brominated and iodated species	CH_3Br	N	T(OH)	1.7	0.01	0.01	0.01 - 0.02	Major natural bromine carrier
	$CBrF_3$(F13B1)	A	S(UV)	110	0.001	0.005	0.003- 0.01	Fire extinguisher
	CH_2BrCH_2Br	A	T(OH)	0.4	0.002	0.002	0.001- 0.01	Major gasoline additive for lead scavenging; also a fumigant
	CH_2I	N	T(UV)	0.02	0.002	0.002	--	Exclusively of oceanic origin
Hydrocarbons CO, H_2	CH_4	N	T(OH)	5-10	1650	2340	1850 - 3300	A trend showing increase over the last 2 years has been identified
	C_2H_6	N	T(OH)	0.3	0.8	0.8	0.8 - 1.2	Predominantly of auto exhaust origin
	C_2H_2	A	T(OH)	0.3	0.06	0.1	0.06 - 0.16	No trend has been identified to date
	C_3H_8	N.	T(OH)	0.03	0.05	0.05	0.05 - 0.1	No trend has been identified to date
	CO	N.A	T(OH)	0.3	90	115	90 - 160	No trend has been identified to date
	H_2	N.A	T(SL.OH)	2	560	760	560 - 1140	
Ozone	O_3 (Tropospheric)	N	T(UV, SL,O)	0.1-0.3	F(Z)**	12.5%		A small trend appears to exist but data are insufficient
Aldehydes	HCHO	N	T(OH,UV)	0.001	0.2	0.2	--	Secondary products of hydrocarbon oxidation
	CH_3CHO	N	T(OH,UV)	0.001	0.02	0.02	--	1980 concentration estimated from theory

*N - Natural; A - Anthropogenic; O - Oceanic; S - Stratosphere; UV - Ultraviolet Photolysis; T - Troposphere; OH - Hydroxyl radical removal; I - Ionospheric and extreme UV and electron capture removal; SL - Soil sink

+These concentrations are integrated averages; for chemicals with lifetimes of 10 years or less, significant latitudinal gradients can be expected in the troposphere; for chemicals with extremely short lifetimes (0.001-0.3 years) vertical gradients may also be encountered

**Varies from 25 ppbv at the surface to about 70 ppbv at 9 km. The concentration was increased uniformly by the same percentage from the surface to 9 km.

***These values are not used in the present assessment.

Source: Ramanathan, Cicerone, Singh, and Kiehl (1985)

Table 2-2. Radiative Forcing for a Uniform Increase in Trace Gases

Compound	Radiative Forcing (°C/ppb)
CO_2	.000004
CH_4	.0001
N_2O	.001
CFC-11	.07
CFC-12	.08
CFC-13	.10
Halon 1301	.10
F-116	.08
CC14	.05
CHC13	.04
F-14	.04
HCFC-22	.03
CH2 C12	.02
CH3 CC13	.01
C2 H2	.01
SO2	.01

Source: Adapted from Ramanathan et al. (1985).

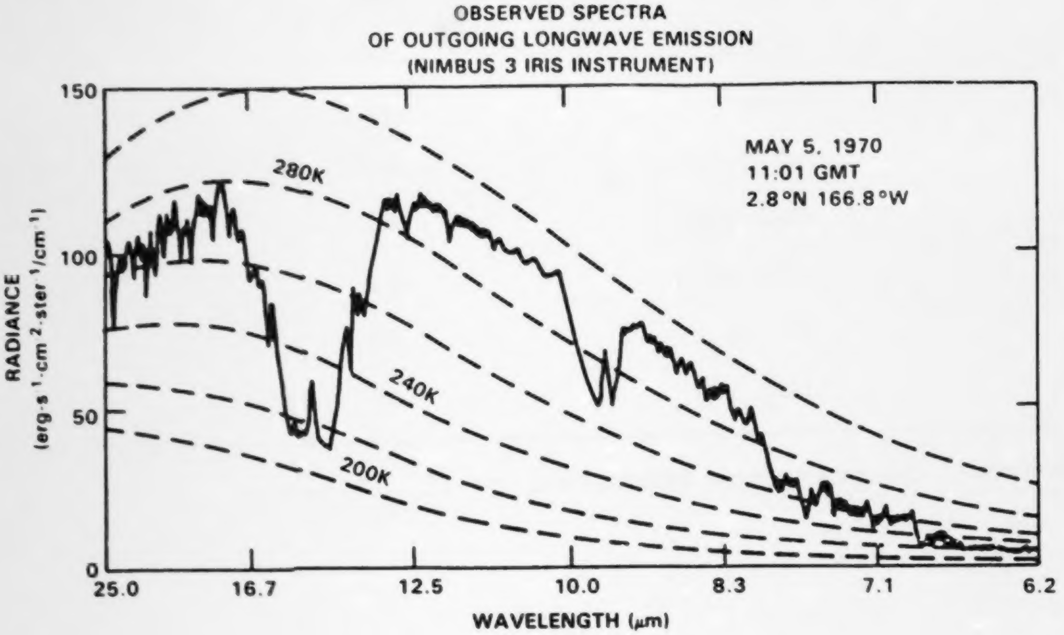

Figure 2-2. Sample spectra from the IRIS instrument on board NIMBUS-3 satellite. The dashed lines indicate the effective radiation temperature for different wave lengths.

Source: Hanel et al. (1972).

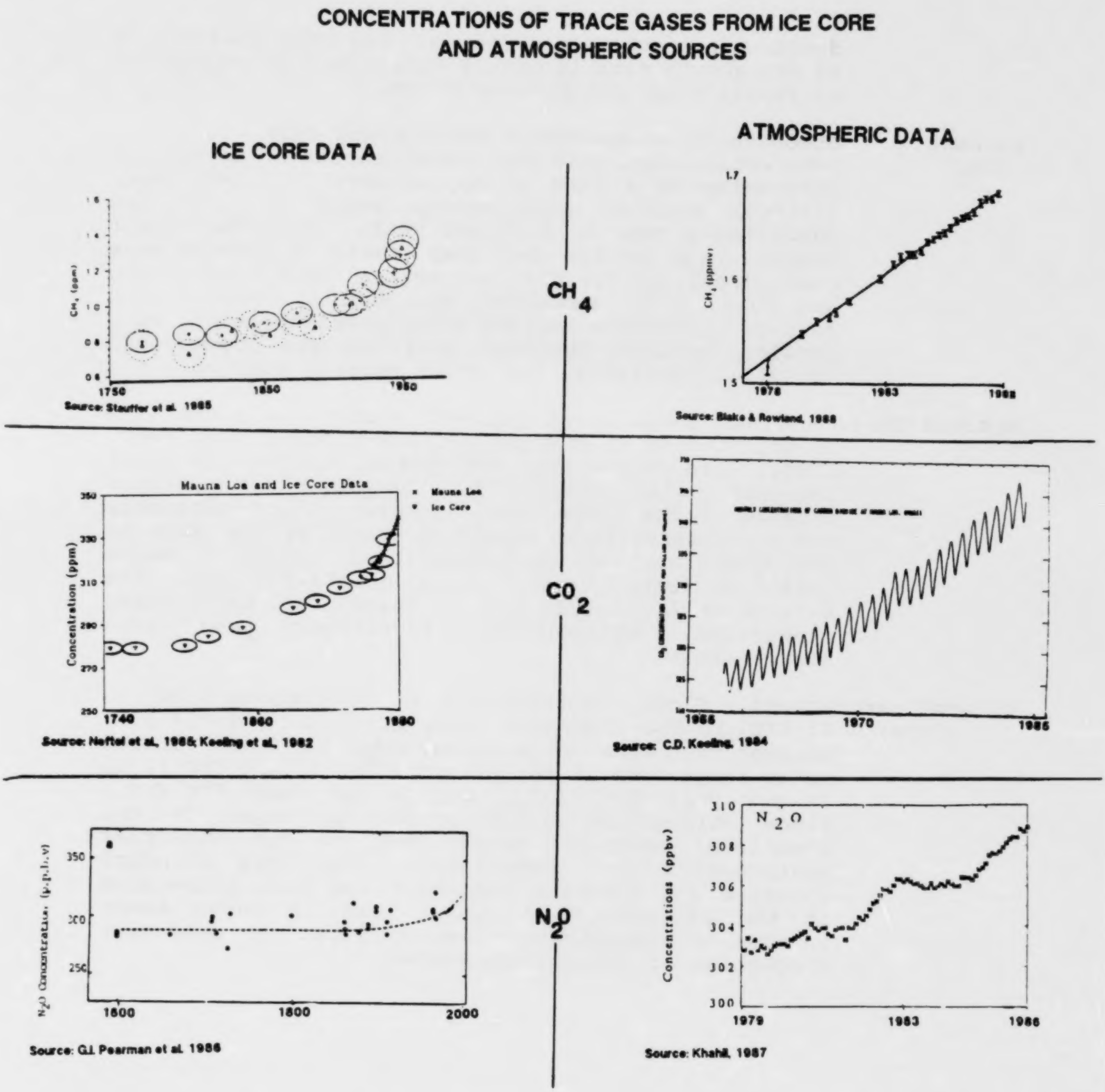

Figure 2-3. Greenhouse gas trends in ice cores and atmospheric instrument data.

decades is about 15 ppm/decade. The near quadrupling of the growth rate is mainly attributed to combustion of fossil fuel and deforestation.

Methane - (CH_4) Atmospheric measurements taken since 1979 have established that the concentration of methane is increasing at a rate of approximately 1% per year, although earlier measurements begun in 1965 had suggested a rate of 1.8% per year. Analyses of air trapped in polar ice show that levels of methane have been increasing for the last several centuries (Craig and Chou, 1982; Rasmusson and Khalil, 1984). The sources of methane include enteric fermentation, rice paddies, biomass burning, coal and gas production, landfills, wetlands, and other natural sources.

Nitrous Oxide - Recent measurement suggests that N_2O is increasing in the atmosphere at a rate of 0.2-0.3% per year (WMO, 1986). The mean global concentration of N_2O is about 300 ppb, with very little geographic variations because of the gas's long lifetime. There currently are no observations providing quantitative data on preindustrial N_2O concentrations, although Weiss (1981) estimated concentration of 281-291 ppb. The sources of N_2O include oceans, fossil fuel and biomass combustion, agricultural fertilizers and land disturbances.

Chlorofluorocarbons - (CFCs) Global measurements of halocarbons (CFC-11($CFCl_3$), CFC-12(CF_2Cl_2), CCl_4 and CH_3CCl_3) since 1978 suggest that each gas is increasing with time. Growth rates range from 5% per year for CFC-11 and CFC-12 to 7% per year for CH_3CCl_3 and 1% per year for CCl_4. Since chlorofluorocarbon production began in the twentieth century, there are no preindustrial measurements for comparison. The less abundant chlorine and fluorine compounds are also increasing in the atmosphere, although less is known about changes in atmospheric concentrations. An extensive discussion of chlorofluorocarbon sources including refrigerants, aerosols, sprays, insulating material and solvents is contained in EPA (1987).

Ozone - An important greenhouse gas/ozone, plays a major role in the chemistry of the stratosphere and the troposphere. Current understanding of atmospheric chemistry suggests that hydrocarbons, carbon monoxide, and methane act to increase the abundance of tropospheric ozone by suppressing ohydroxyl radicals (Thompson, 1986). There are data and theories that suggest that ozone in the free troposphere is increasing with time, perhaps at a rate of 0.5 to 1% per year (Logan, 1982; Angell and Kovshover, 1983). Ramanathan estimated that perhaps ozone increased by about 25% between 1880 and 1980. Extensive analysis with stratospheric models suggest that CFCs act to deplete stratospheric ozone. Hence, there are counterbalancing global trends and important differences between the stratosphere and the troposphere, as well as differences between regions (WMO, 1986). The net effect on climate may be a warming due to the greater greenhouse effect of tropospheric ozone, (Ramanathan and Dickensen, 1979), but important research questions remain to be answered.

Other Gases - Carbon Monoxide (CO_2) Nitrogen Oxides (NO_x)
Other gases play an important role in the balance of the earth's radiation. In particular, carbon monoxide (CO) and nitrogen oxides (NO_x) affect both methane and tropospheric ozone. One study by Rasmussen and Khalil, (1984), indicated CO increases of about 5% per year. Results by Dorgashina et al. (1984) suggest a 1-2% per year increase. Important sources of CO include fossil fuel combustions, oxidation of natural hydrocarbons and CH_4, and burning of savanna, agricultural land, and forests There is no direct evidence to define the history of CO over the past centuries, but a number of factors, such as the north/south gradient, suggest that an increase by a factor of two may have been possible since prehistoric times (WMO, 1986). Measurement of nitrogen species, NO_x and ammonia in the troposphere are few in remote regions. These species have very short lifetimes (0.5 to 5 days). While global levels of NO_x are certainly higher than in preindustrial times, the total impact of man's activities on NO_x remains unclear.

RADIATIVE FORCING AND CLIMATE SENSITIVITY

The biochemical and physical processes that change the fluxes of radiative energy into and out of the surface-atmosphere system are generally referred to as radiative-forcing factors. If the process tends to warm the earth-atmosphere system, the forcing is deemed to be positive. The greenhouse gases discussed in the previous section exert a positive radiative forcing, as do high clouds. If the process tends to cool the earth-atmosphere system, the forcing is deemed to be negative. Examples of negative radiative forcing include stratospheric aerosols from volcanos and low clouds. The potential radiative effect of various climate-forcing factors based on model analysis by Hansen as modified in WMO, 1986, is shown in Figure 2-4.

At present the direct climate forcing from increasing greenhouse gases is not large enough to completely dominate other forcing factors, such as stratospheric aerosols and solar irradiance (the total energy from the sun) (Hansen, 1987a). For example, solar irradiance was observed to decrease by approximately 0.09% between 1979 and 1985. This negative forcing is somewhat larger than the positive forcing from CO_2 increases during the same Figure period. An even larger negative forcing occurred during 1982-84 as a result of stratospheric aerosols generated by the volcano El Chichón. Volcanos can eject sulfuric acid aerosols and other particles high into the stratosphere. Ramanathan (1988) estimated that a major eruption such as El Chichón could contribute cooling that would nearly equal the trace gas warming for the period 1975-85. These climate forcings can mask the effect of man-induced greenhouse gases for periods ranging from a few years to decades. But over a long period, such natural factors as volcanoes should have no lasting effect.

Other climate forcing, such as changes in tropospheric aerosols or surface albedo are also potentially important, particularly on a regional basis. Examples of changing aerosols abundance include arctic haze, desert aerosols, and urban/rural aerosols. Changes in albedo variations may be associated with large-scale changes in land use (deforestation) or the latitudinal extent of sea ice and snow cover as global warming occurs.

ROLE OF ATMOSPHERIC MODELS

Scientists attempt to understand how the earth-atmosphere system works by building mathematical models of different complexity. The simplest approach that allows an understanding of the radiative and chemical processes is a one-dimensional (1-D)

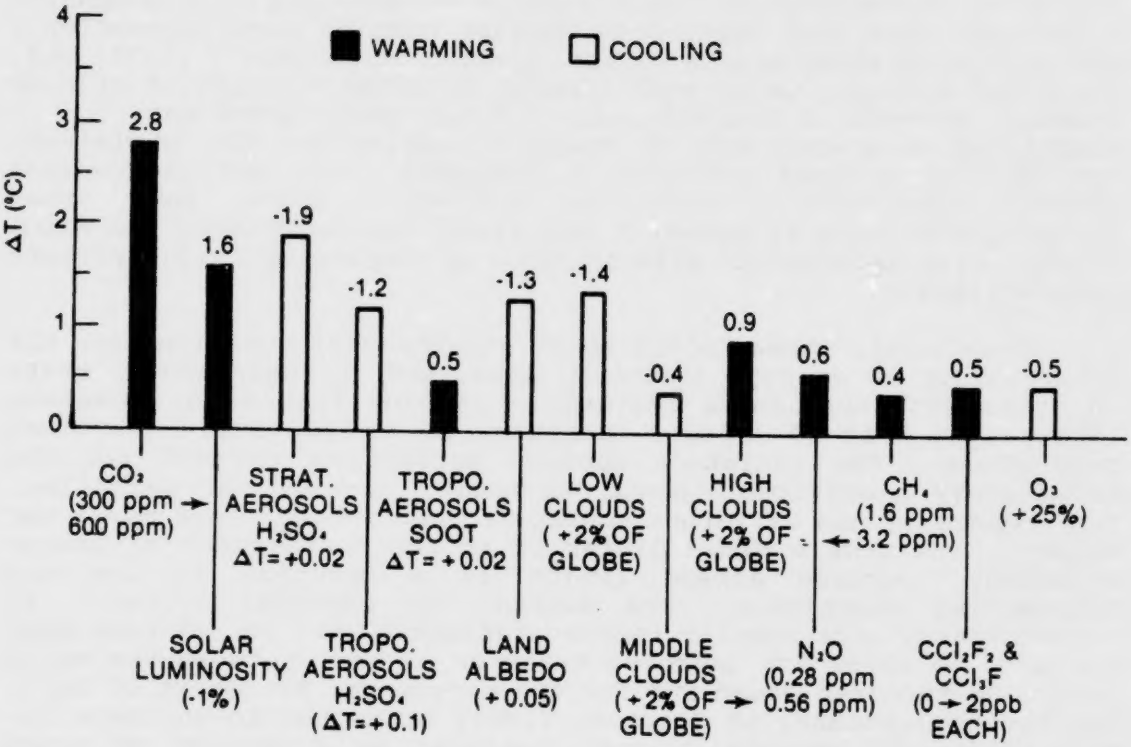

Figure 2-4. One dimensional radiative-convective model estimates of surface temperature effects of various global radiative perturbations. All of the results, except for CH_4, and the figure are adapted from Hansen et al., 1981. The CH_4 result was obtained as follows: The radiative forcing of doubled CH_4 as given in WMO (1982) is multiplied by the climate sensitivity of Hansen et al. (1981) model to obtain T_s.

model. This type of model allows no horizontal variations and, hence, is only useful for obtaining globally averaged results or results over some particular location. Nevertheless, it is an important tool that allows investigators to quickly conduct experiments that serve as a basis for more complex models.

Conducting analyses of the type discussed in this report necessitates having climate data sets for temperature, winds, precipitation, and other variables for different regions of the country and globe. The development of such data requires that the chemical and dynamic processes of the entire earth-atmosphere system be represented as realistically as practical. Atmospheric scientists have been working to develop complex three-dimensional general-circulation models (GCMs). Manabe and Wetherald (1975) made the first attempt, using such a model to study CO_2-induced climate change. Because of computational limits, their model had simplified geography and no seasonal variations in insolation. However, it yielded preliminary insights into how latitudinal climate variations could be deduced. Since then other investigators such as Hansen et al. (1984) and Washington and Meehl (1983), have used models with increasing complexity to investigate future climate.

In general, these models solve simultaneous equations for the conservation of energy, momentum, mass, and the equation of state on grids with horizontal resolution ranging from 4 to 8 degrees latitude by 5 to 10 degrees longitude, and with varying vertical resolution. The radiation schemes attempt to account for the radiatively significant gases, aerosols, clouds, and particles. They generally use different schemes for computing cloud cover and height. The models often differ in in their treatment of ground hydrology, surface albedo (which is a function of ice and terrestrial vegetation), and diurnal and seasonal cycles. In recent years, more complex representations of the oceans have been included to allow for improved transfer of heat between the mixed layer and the deep ocean and for the horizontal transport of heat. The National Academy of Sciences (1987) attempted to evaluate the probability of certain climate features as a result of model analyses. The results shown in Table 2-3 suggest that such features as increased polar warming and increased global precipitation are probable in a doubled CO_2 world. However,

Table 2-3. Summary of Scientific Confidence

Large Stratospheric Cooling (virtually certain). Reduced ozone concentrations in the upper stratosphere will lead to reduced absorption of solar ultraviolet radiation and therefore less heating. Increases in the stratospheric concentration of carbon dioxide and other radiatively active trace gases will increase the radiation of heat from the stratosphere. The combination of decreased heating and increased cooling will lead to a major lowering of temperatures in the upper stratosphere.

Global-Mean Surface Warming (very probable). For an equivalent doubling of atmospheric carbon dioxide, the long-term global-mean surface warming is expected to be in the range of 1.5 to 4.5°C.

Global-Mean Precipitation Increase (very probable). Increased heating of the surface will lead to increased evaporation and, therefore, to greater global mean precipitation. Some individual regions might well experience decreases in rainfall.

Reduction of Sea Ice (very probable). As the climate warms, total sea ice is expected to be reduced.

Polar Winter Surface Warming (very probable). As the sea ice boundary is shifted poleward enhanced surface warming in winter polar regions is likley. Warming of the polar surface air may be as much as 3 times the global mean warming.

Summer Continental Dryness/Warming (likely in the long term). Several studies have predicted a marked long-term drying of the soil moisture over some mid-latitude interior continental regions during summer. This dryness is mainly caused by an earlier termination of snowmelt and rainy periods, and an earlier onset of the spring-to-summer reduction of soil wetness.

High-Latitude Precipitation Increase (probable). As the climate warms, the increased poleward penetration of warm, moist air should increase the average annual precipitation in high latitudes.

Rise in Global Mean Sea Level (probable). A rise in mean sea level is generally expected due to thermal expansion of sea water in the warmer future climate. Far less certain is the contribution due to melting or calving of land ice.

Source: Modified from NAS (1987) (The original text should be consulted to understand the context completely.)

improved understanding of ocean circulation processes and the coupled ocean-atmospheric system is necessary before the climate system can be completely understood.

For comparative purposes, the global surface air temperature changes induced by seven GCMs for a doubled CO_2 concentration are presented in Table 2-4. The first four models show changes ranging from 1.3 to 3.0°C with the lower values generally associated with simple ocean models with zero heat capacity and no horizontal or vertical heat transport. The studies with higher values were conducted with fixed-depth oceans that have heat capacity and prescribed horizontal heat transports. This range of results is reflected in the National Academy of Sciences' 1987 report, which reaffirmed that a 1.5 to 4.5°C increase in global temperatures is likely under doubled CO_2 conditions. A more recent review by Dickenson (1986); recommended a 1.5 to 5.5°C increase, and a paper by Lashof (1988) suggests that when all biogeochemical feedbacks are considered a temperature sensitivity of as much as 8 to 10°C may be possible.

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Uncertainties in General Circulation Models

The introduction of greenhouse gases into the atmosphere causes the earth's system to seek a new equilibrium in several ways. Often called climate feedbacks, these responses include changes in water vapor, ice cover albedo, clouds, and the oceans. Among these, the water vapor feedback is the most important, since it amplifies surface warming by about 50 to 80 percent. In general, the increase in trapped infrared radiation warms the troposphere and the oceans, causing moisture to evaporate, which further enhances greenhouse warming. Another important effect is the ice-snow albedo feedback. This process focuses on the melting

Table 2-4. Surface Air Temperature Change Induced by a Doubled CO_2 Concentration as Simulated by Selected General Circulation Models

Study	T_s (K)
Manabe & Wetherald (1975)	2.9
Manabe & Wetherald (1980)	3.0
Schlesinger (1983)	2.0
Washington & Meehl (1983)	1.3
Washington & Meehl (1984)	3.5
Hansen et al. (1984)	4.2[2]
Manabe & Wetherald	4.0

Source: World Meteorological Organization (1986).

of ice and snow and the changes in absorbed solar radiation, which amplify initial warming. This feedback amplifies global warming by only 10 to 20 percent, but near the sea-ice margins, the warming can be two to five times larger. Therefore, this process is an important contributor to the larger temperature increases predicted by general circulation models for polar regions.

Cloud Feedbacks

The increased water vapor from the oceans should also alter cloud distributions and height. The exact nature of future cloud changes -- i.e., whether more clouds will form and at what altitude -- remains unclear. Somerville and Remer (1984) have proposed a process by which clouds could reduce warming by increasing their optical thickness. Recent observations by the International Satellite Cloud Climatology project, which seeks to collect global data on clouds, suggest that warmer tropical regions typically have more cirrus clouds that trap greater amounts of infrared radiation.

After water vapor, clouds play the next most important role in the energy balance of the earth-atmosphere system. They could either enhance or partly negate greenhouse warming, but are unlikely to completely reverse the effect of greenhouse gases. While the temperature sensitivity of current GCMs increases with the introduction of interactive clouds, we have much to learn about cloud processes before we can make reliable conclusions about the nature of cloud feedback processes.

Ocean Processes - The Timing of Global Warming

The oceans play an important role in the climate change process in several ways. First, they absorb CO_2, with most estimates suggesting that approximately 50 percent of past CO_2 emissions are sequestered in the ocean. And second, they absorb heat into their deeper layers, thereby delaying global warming. A more thorough discussion of the CO_2 and the oceans can be found in EPA (1989).

A key policy question asked by decision makers is, How soon will global warming take place? To estimate the rates of future warming, Hansen (1984,) used a one-dimensional radiative convective model coupled to an ocean box-diffusion model. The scenarios used for trace gas growth are generally the same as those discussed in other chapters of this report. The results shown in Figure 2-5 suggest approximately a 30-to 40-year delay in the full magnitude of global warming. Although response times as rapid as 10 years may be possible for climate sensitivities as low as 2°C, and as slow as a 100 years for a sensitivity of 5°C. Hansen describes the

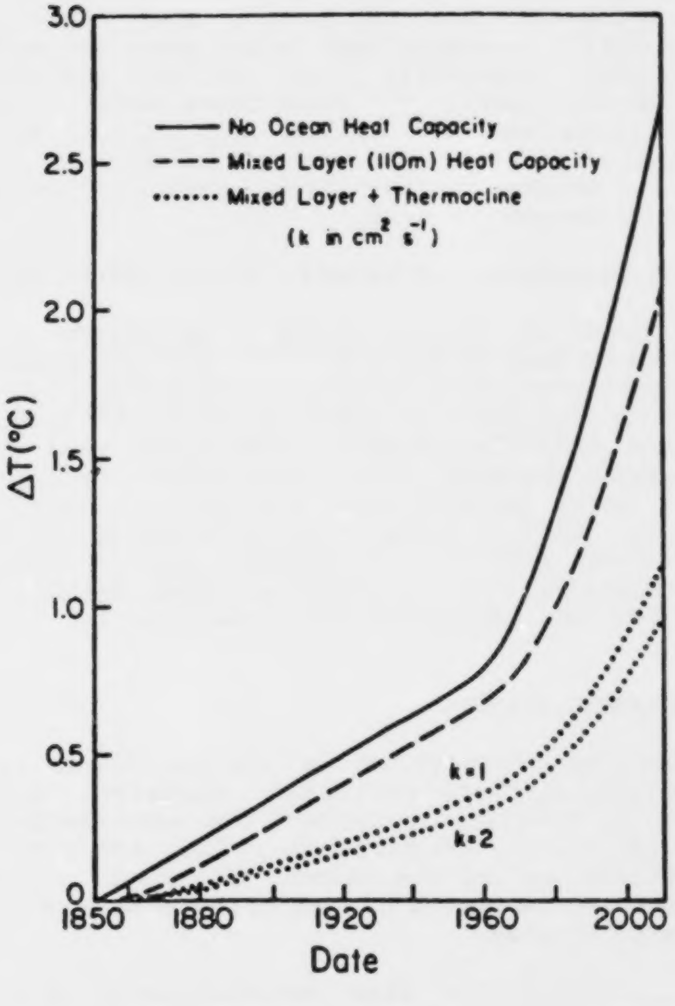

Figure 2-5. Transient estimates of global warming.

Source: Hansen (1984).

growing gap between realized warming and equilibrium warming, and suggests that the warming already built into the system, but not yet evident, may need to be considered in setting national policies.

Models such as this can neither portray complex connections and diverse processes that govern the exchange of heat in the oceans, nor represent the topography and water densities in different regions. Attempts are being made to model the ocean differently or more completely (e.g., Hoffert and Flannery, 1985; Sarmiento and Bryan, 1982). But even these models will not capture the potential surprises the oceans may hold. Broecker (1987) argues that there is clear evidence that changes in the earth's climate can be sudden rather than gradual, as suggested by experiments with current models.

Regional Intercomparisons of General Circulations Models

The Department of Energy recently sponsored a study of the results produced by four different general circulation models (DOE, 1988). The study examined results of both surface air temperatures and precipitation for both current climate and doubled CO_2. The study points out that the models often agree well when comparing seasonal or annual averages over large areas (Figures 2-6 and 2-7), but do not agree as well when the spatial extent is reduced. (See Table 2-5) Collectively, the results point out important differences between models, and suggest caution when using model results for estimating climate impacts. (See Chapter 3 for further discussion of the use of models and scenarios.)

EVIDENCE of CLIMATE CHANGE

A key question often asked is whether there is evidence to suggest that global climate is already changing. A comprehensive response to this question requires the examination of several climate variables (e.g., temperature, wind, and precipitation) at different locations around the globe. The most comprehensive data set used to measure the state of the climate system is global mean surface air temperatures.

Several investigators used meterological data to examine temperature change during the last century (Bradley et al., 1985). The results by Hansen and Lebedeff (1987) indicate a global warming of about 0.5 to 0.7°C in the past century, with warming of similar magnitude in both hemispheres (Figure 2-8). Hansen and Lebedeff also found that eliminating urban stations to account for possible heat island effects reduced these values by about 0.1°C. Jones et

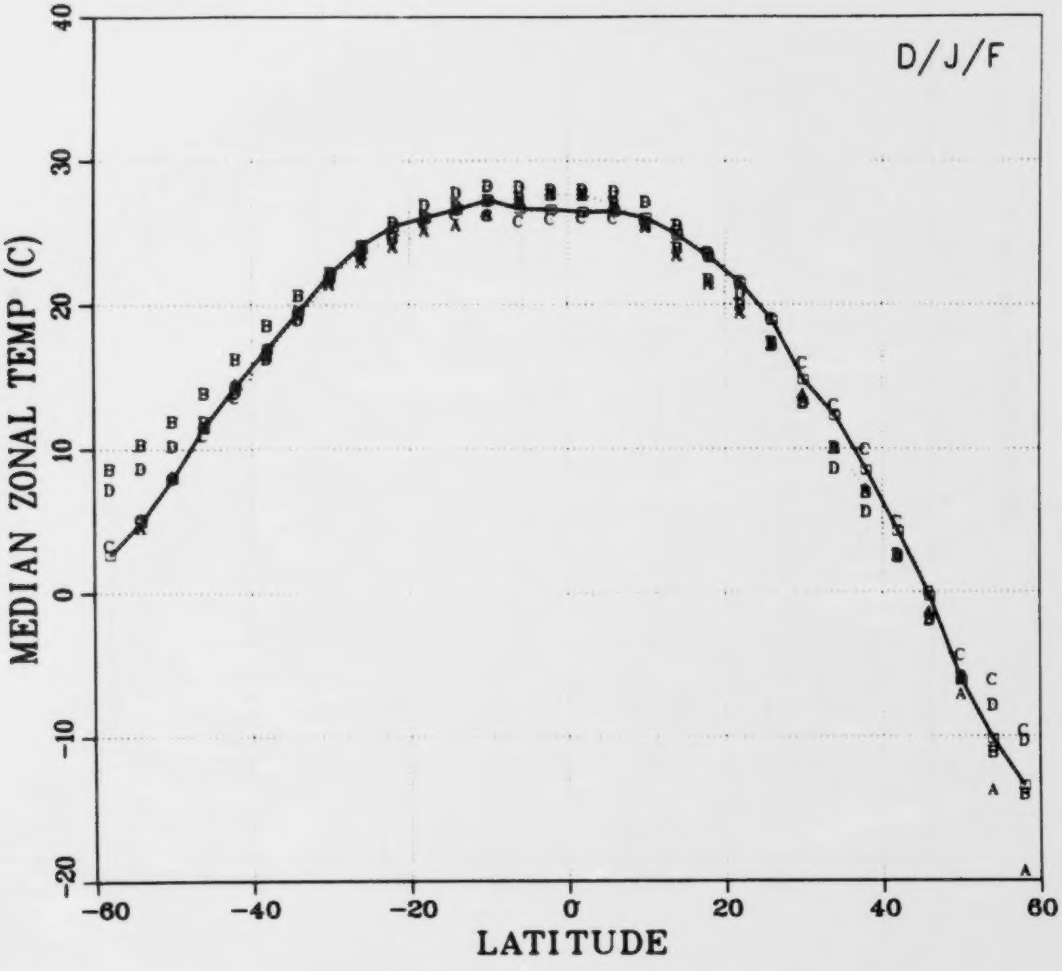

Figure 2-6. Zonal average December, January and February control temperatures for four GCMs and historical data (solid line) A=CCM, B=GFDL, C=GISS, D=OSU.

Source: DOE Report, "Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data." April, 1988. S. Grotch.

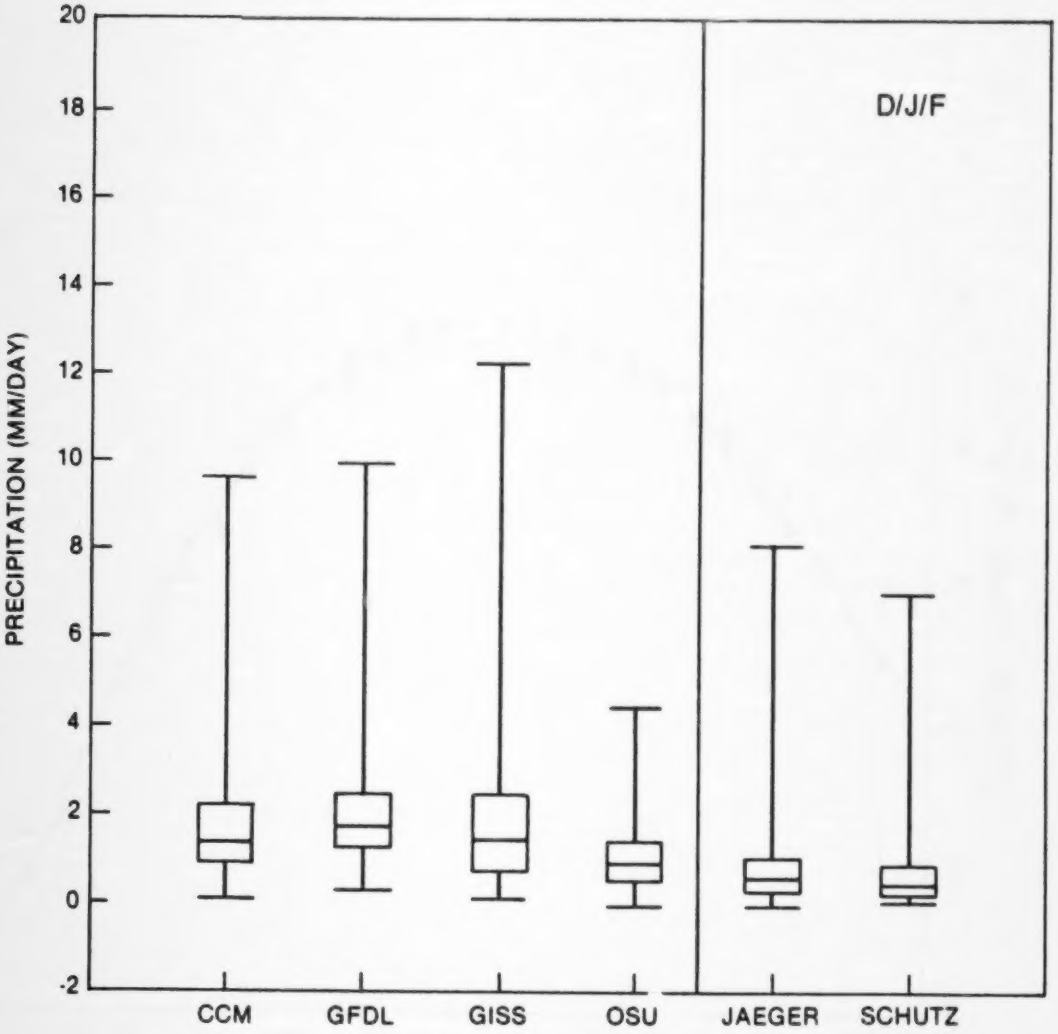

Figure 2-7. Seasonal control precipitation (mm/day) over NH land areas as predicted by the GCMs and the Jaeger and Schutz-Gates Historical Gridded Data Sets for December, January and February.

Source: DOE Report, "Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data." April, 1988. S. Grotch.

Table 2-5. Seasonal Comparison of Observed and Modeled Control Temperature for Different Geographical Regions

Variable and Model	Domain of Comparisons Global	North America	Contiguous U.S.	Midwestern U.S.
	December-January-February			
Observed Median Temperature (°C)	8.5	-5.8	0.9	-1.5
Difference in Median Temperatures (GCM - Observation)				
CCM	1.6	0.3	-2.1	-0.5
GFDL	1.5	1.8	-0.8	-1.3
GISS	0.8	-0.5	0.0	1.1
OSU	0.3	0.5	-0.6	-1.0
	June-July-August			
Observed Median Temperature (°C)	13.9	18.9	23.0	23.0
Difference in Median Temperatures (GCM - Observation)				
CCM	1.3	6.0	6.3	6.8
GFDL	-0.2	0.6	0.1	3.7
GISS	0.4	-3.1	-4.5	-4.8
OSU	-0.6	-2.2	-2.2	-1.6

Source: DOE Report, "Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data" April, 1988. S. Grotch.

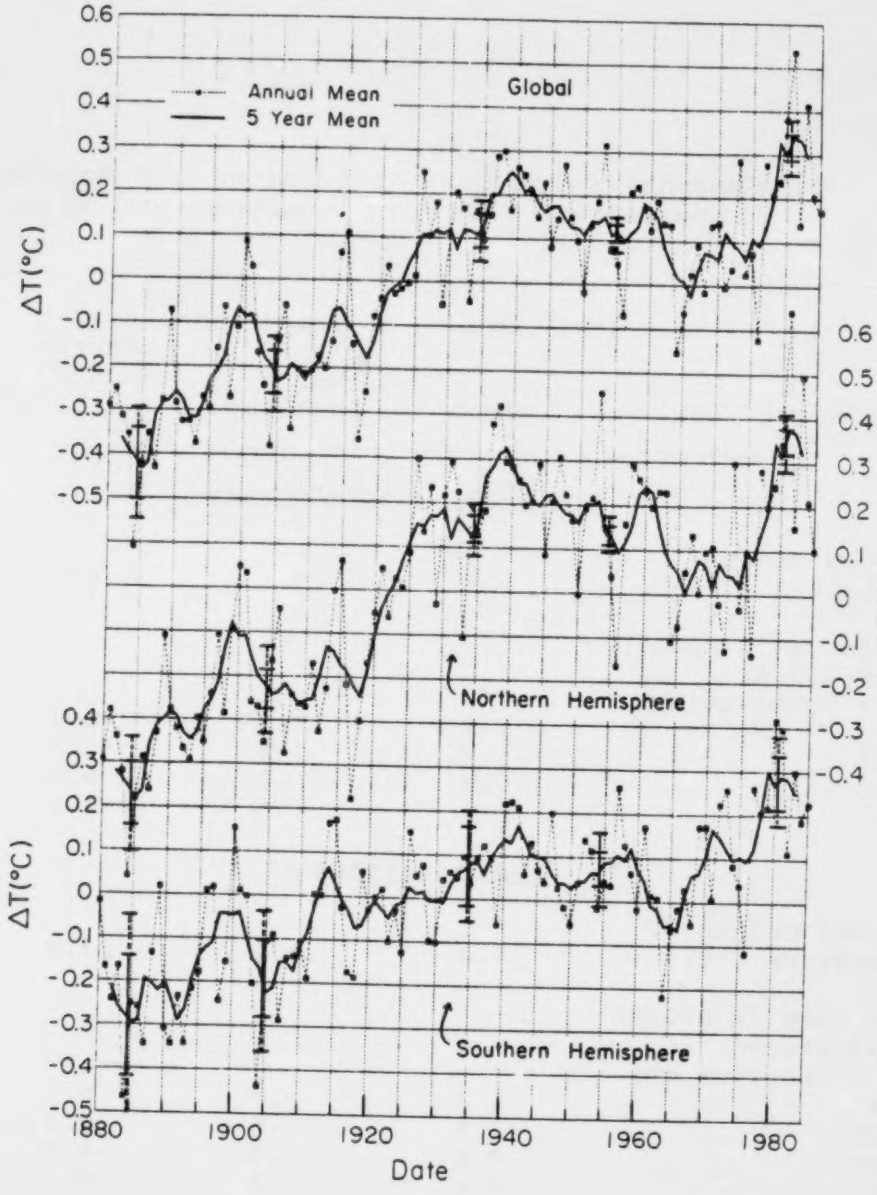

Figure 2-8. Global and hemispheric surface air temperature change estimated from meteorological station records. The northern hemisphere scale is on the right. The 5-year running mean is the linear average for the 5 years centered on the plotted year. The uncertainty bars (95% confidence limits) are based on the error analysis in Section 5; the inner bars refer to the 5-year mean and the outer bars to the annual mean.

Source: J. Hansen, and S. Lebedeff. "Global Trends of Measured Surface Air Temperature." J. Geophys. Res. vol. 92, November 20, 1987:13,351.

al. (1982) found similar trends for sea surface temperatures beginning in 1861 and noted that the warmest three years have occurred in the 1980s. (The very warm year of 1987 subsequently suggests that the warmest four years have occurred in the 1980s). Jones et al.'s results show little trend in the nineteenth century, marked warming to 1940, relatively steady conditions to the mid-1970s, and a subsequent rapid warming up to the present.

Temperature changes in the upper atmosphere were reported by Angell (1983). More recently, NASA (1988) examined satellite, radiosonde, and rocketsonde data on temperatures in the stratosphere at various altitudes. Radiosonde analysis from 1970 to the present show no significant trends in temperature below 30 mb, except in equatorial and Antarctic regions. During 1979-1986, while accounting for the El Chichón volcano effects, global temperatures show a decline between 1.75°C at 0.5 mb (45-55km) to 1°C below 5 mb. These actual temperature trends are less than current model predictions, but are in the same direction predicted by theory.

Lachenbruch and Marshall (1986) examined temperature changes in the arctic region by conducting temperature measurements in permafrost in northern Alaska. The advantage of permafrost records is that they represent a systematic record of recent history and a relatively smooth signal of temperature change. Their results indicate a variable but widespread warming of the permafrost in the range of 2 to 4 °C during the last few decades to a century. While more extensive measurements are needed to assess changes in this region, the results appear to be generally consistent with model predictions that suggest more rapid warming in polar regions.

Finally, there is remarkable evidence, based on ice core records that document the long-term changes in temperatures and their relationship to atmospheric CO_2 concentrations. The Vostok ice core records by Barnola et al. (1987) provide direct evidence of these trends over the last 160,000 years. The record in Figure 2-9 shows two very large increases in temperature and CO_2. One occurred approximately 15,000 years ago, corresponding to a jump from approximately 220 ppm CO_2, and another occurred nearly 140 thousand years ago. The high CO_2 level of approximately 280 ppm, corresponds to the preindustrial CO_2 concentrations that prevailed until 100-300 years ago. The low CO_2 concentrations generally correspond to the glacial conditions that prevailed for most of the last 100,000 years. While it is difficult to assign a cause for these past changes, it is reasonable to conclude that, given current CO_2 concentrations of 345 ppm, global temperatures will soon equal or exceed the maximum temperatures of more than 100,000 years ago.

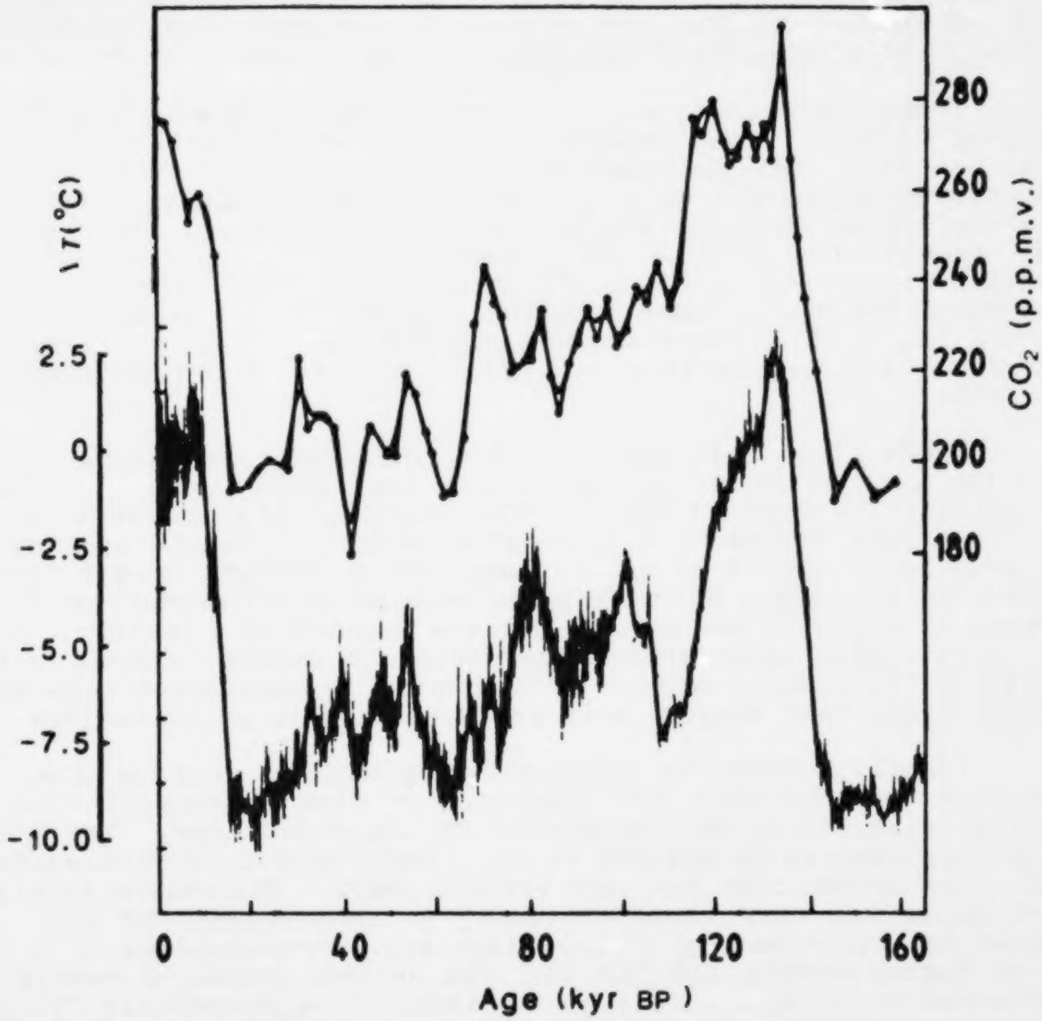

Figure 2-9. Carbon dioxide levels and temperatures over the last 160,000 years. From Vostok 5 Ice Core.

Source: Barnola et al. (1987).

REFERENCES

Angell, J.K. and Korshover, J. 1983. Global Variations in total ozone and layer - mean ozone: An update through 1981, Journal of Climate and Applied Meteorology, 22, 1611-1627.

Angell, J.K. and Korshover. 1983. Global temperature variations in the troposphere and stratosphere 1985-1982, Monthly Weather Review 111, 901-921.

Barnola, J.M., Raymond, D., Korotkevich, Y.S., Lorius, C. 1987. Vostok ice core provides 160,000 year record of atmospheric CO_2 Nature 32, 408-414.

Blake, Donald R. and F. Sherwood Rowland. 1988. Continuing Worldwide Increase in Tropospheric Methane, 1978 to 1987. Science 239:1129-1131.

Bradley, R.S., Kelly, P.M., Jones, P.D., Goodess, C.M., and Diaz A.F. 1988. A Climatic data bank for northern hemisphere land areas 1985-1980. DOE Tech. Report 117. (DOE/EV/10739-2). Dept. of Energy, Washington, D.C.

Broecker, W. 1987. "Unpleasant surprises in the Greenhouse?" Nature 328, 123-126.

Craig H. and Chou C.C. 1982. Methane: The Record in Polar Ice Cores, Geophysical Research Letters, 9, 1221-1224.

Department of Energy. 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. DOE/NBB-0084.

Dickenson, R.E. 1986. The climate system and modeling of future climate in The Greehouse Effect, Climate Change and Ecosystems, eds. B. Bolin, B.A. Doos, J. Jager and R.A. Warrick, Wiley Press, New York, pp. 206-270.

Dvoryashina, Y.V., Dianov, V.I. and Yurganov, L.N. 1984. On the variations of atmospheric total column carbon monoxide abundance for 1970-1982, Physical Atmosphere Oceans, 20,40-47.

Environmental Protection Agency. 1987. Assessing the Risks of Greenhouse gases that Can Modify the Stratosphere. EPA 400-1-87/001C Vol. I-VI. Washington, D.C.

Hansen, J., Fung, I., Lacis, A., Lebedeff, S., Rind, D., Ruedy, R., Russell, G., and Stone, P. 1987. Prediction of Near Term Climate Evolution: What Can We Tell Decision Makers Now? First North American Conference on Preparing for Climate Change, Washington, D.C.

Hansen, J., and Lebedeff, S. 1987. Global Trends of Measured Surface Air Temperature, Journal of Geophysical Research, 92, 13,345-372.

Hansen, J. Lasis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R., and Lerner, J. 1984. Climate Sensitivity: Analyses of Feedback mechanisms in Climate Processes and Climate Sensitivity, Maurice Ewing Series, 5. eds. J. Hansen and T.Takahasi. American Geophysical Union, p. 368, Washington, D.C.

Hansen, J. Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., and Travis, L. 1983. Efficient three-dimensional global models for climate studies: Model I and II Monthly Weather Review 111, 609-662.

Hoffert, M.I., and Flannery, B.B. 1985. Model Projections of the Equilibrium Climatic Response to Increased Carbon Dioxide, in MacCracken, M.C., and F.M. Luther Projecting the Climatic Effects of Increasing Carbon Dioxide. DOE/ER-0237, U.S. Dept. of Energy, Washington, D.C.

Jones, P.D., Wigley, T.M. and Wright, P.B. 1986. "Global Temperature Variations between 1861 and 1984." Nature 322, 430-434.

Jones, P.D., Wigley, T., and Kelly, P.M. 1982. "Variations in Surface Air Temperatures: 1 Northern Hemisphere, 1881-1980, Monthly Weather Review 110, 59-70.

Keeling, C., R. Bacastow, and T. Whorf. 1982. Measurement of the concentration of carbon dioxide at Mauna Loa Observatory, Hawaii. In W. Clark, ed., Carbon Dioxide Review: 1982. pp. 377-384.

Keeling, Charles D. and Alane F. Carter. 1984. Seasonal, Latitudinal, and Secular Variations in the Abundance and Isotopic Ratios of Atmospheric CO2. Results From Oceanographic Cruises in the Tropical Pacific Ocean. Journal of Geophysical Research 9:4615-4628.

Khalil, M., and R. Rasmussen. 1983. Increase and seasonal cycles in the atmospheric concentration of nitrous oxide(N2O). Tellus 35B:161-169.

Lachenbruch, A.H. and Marshall B.V. 1986. Changing Climate: Geothermal Evidence from Permafrost in the Alaska Arctic Science 234, 689-696.

Lashof, D.A. 1988. The Dynamic Greenhouse: Feedback Processes that May Influence Future Concentrations of Atmospheric Trace Gases, Submitted to Journal of Climate Change.

Logan, J.A. 1982. Paper presented at Second Sumposium on the Composition of the Nonurban Troposphere, Williamburg, Va.

Manabe, S., and Wetherald, R.T. 1975. The effects of doubling CO_2 - concentrations on the climate of a general circulation model. Journal of Atmospheric Sciences 32, 3-15.

National Academy of Sciences (NAS). 1979. Carbon Dioxide and Climate: A Second Assessment, National Academy Press, Washington, D.C.

National Academy of Sciences (NAS). 1979. Carbon Dioxide and Climate: A Scientific Assessment, National Academy Press, Washington, D.C.

National Academy of Science (NAS). 1987. Current Issues in Atmospheric change National Academy Press, Washington, D.C.

National Aeronatics and Space Administration. 1988. Ozone Trends Panel Report.

Neftel, A., E. Moor, H. Oeschger, B. Stauffer. 1985. Evidence from polar ice cores for the increase in atmospheric CO2 in the past two centuries. Nature 315: 45-47.

Pearman, G., D. Etherridge, F. de Silva, and P. Fraser. 1986. Evidence of Changing concentrations of Atmospheric CO2, N2O, and CH4 from Air Bubbles in Antartic Ice. Nature, vol.320:248-250.

Ramanathan, V. 1988. The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment. Science 240, 293-299.

Ramanathan, V. and Dickinson, R.E. 1979. The role of stratospheric ozone in the zonal and seasonal radiative energy balance of the earth-troposphere system. Journal of Atmospheric Sciences, 36, 1084-1104.

Ramanathan, V., R.J. Cicerone, H.B. Singh, and J.T. Kiehl. 1985. "Trace Gas Trends and Their Potential Role in Climate Change." Journal of Geophysical Research, 90(D3): 5557-5566.

Rasmussen, R., Khalil M.A.K. 1984. Atmospheric Methane in Recent and Ancient Atmospheres: Concentrations, Trends and Interhemispheric Gradients, Journal of Geophysical Research, 89 11599-11605.

Sarmiento, J., and Bryan, K. 1982. "An Ocean Transport Model for the North Atlantic." Journal of Geophysical Research 87, 9694-9698.

Somerville, R.C.J. and L.A. Remer. 1984. "Cloud Optical Thickness Feedbacks in the CO_2 Climate Problem." Journal of Geophysical Research 89, 9668-9672.

Stauffer, B., G. Fischer, A. Neftel, and H. Oeschger. 1985. Increase in Atmospheric Methane Recorded in an Antarctic Ice Core. Science 229:1386-1388.

Stone, P. 1985. Climate Response Times: Dependence on Climate Sensitivity and Ocean Mixing Science 229, 857-859.

Thompson, A.M., Cicerone, R.J. 1986. Possible Perturbations to Atmospheric CO, CH_4, OH. Journal of Geophysical Research, 91, 10,853-10,864.

Tyndall, J. 1961. "On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Coxection of Radiation, Absorption and Conduction, "Philosophical Magazine and Journal of Science 22(146): 169-194.

Wang, W.C., Wuebbles, D.J., Washington, W.M., Isaacs, R.G., Molnar, G. 1986. Trace Gas Trends and Other Potential Perturbations to Global Climate. Review of Geophysics 24(1): 110-140.

Washington, W.M., and Meihl, G.A. 1983. General circulation model experiments on the climate efforts due to a doubling and a quadrupling of CO_2 concentrations, Journal of Geophysical Research 88, 6600-6610.

Weiss, R.F. 1981. The Temporal and Spatial Distribution of Tropospheric Nitrous Oxide, Journal of Geophysical Research, 86, 7185-7195.

World Meterological Organization (WMO). 1986. Atmospheric Ozone 1985. Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change, Global Ozone Research and Monitoring Project--Report No. 16, WMO, Geneva, Switzerland.

DRAFT

CHAPTER 3

METHODOLOGY

The basic components in analyzing the potential effects of global warming include assumptions of how climate will change and approaches to estimate effects that will occur as a result of those changes.

SCENARIOS OF CLIMATE CHANGE

Need for Scenarios

At this time, scientists are unable to reliably predict how the greenhouse effect may change regional climate. Unknown factors include the amount that temperature will rise in certain regions, whether rainfall will increase or decrease, how winds may shift, or whether storm frequency may change.

Scenarios can help illustrate events that may occur in the future. Scenarios may be used to identify possible effects of climate change and to evaluate responses to those effects. To incorporate uncertainties surrounding regional climate change, regional scenarios should include a variety of potential climatic changes consistent with the state of knowledge regarding global warming. By analyzing many scenarios, scientists may be able to determine the direction and relative magnitude of change. It is important to realize that scenarios are not predictions, and their probabilities are not known.

By using scenarios as inputs into models of ecological and manmade systems, the range of possible climate-induced effects within the systems may be determined. For example, climate scenarios can be used in a hydrologic model of a river basin to examine how the river's flow may change. These models of the relationship between climate and particular systems will be referred to as "effects models."

Scenario Components

To assess the potential effects of global climate change, regional scenarios of such change should have the following characteristics:

1. The scenarios should be consistent with global warming caused by anthropogenic increase in greenhouse gas emissions. A doubling of CO_2 concentrations in the

atmosphere is thought to possibly increase global temperatures by approximately 1.5 to 4.5°C (3 to 8°F). The regional temperature change may be higher or lower as long as it is internally consistent with the global range.

2. The scenarios must include a sufficient number of meteorologic variables to meet the requirements for running effects models. Some models of the relationship between climate and a system only need temperature and precipitation, while others also need solar radiation, humidity, winds, and other variables.
3. The meteorologic variables should be internally consistent. While a scenario is not a prediction, it should at least be feasible. The laws of physics limit how meteorologic variables may change in relationship to each other. For example, if global temperatures increase, global precipitation must also rise.
4. The scenarios should provide meteorologic variables on a daily basis. Many of the effects models used in this study need daily meteorologic inputs.
5. Finally, the scenarios should illustrate what climate would look like on a spatial scale fine enough for effects analysis. Many effects models consider changes in individual stands of trees or farm fields. To run them, scenarios must illustrate how climate may change locally.

Types of Scenarios

Two basic questions must be considered in analyzing the potential impacts of the greenhouse effect: What would be the effects of a large climate change in the future? How quickly will the effects become apparent over time? The first question asks what the world will be like in the future; the second is about the speed of change.

One way of examining the first question is to use scenarios of an equilibrium future climate. Equilibrium is defined as climate that has reached a steady state. The equilibrium climate should be significantly different from today's climate.

A drawback of an equilibrium scenario is that it occurs at an arbitrary point in the future and assumes that the climate has reached a stable level corresponding with the higher concentrations of greenhouse gases. It does not indicate how climate may change between now and the equilibrium condition. Thus, equilibrium scenarios are not useful for determining the sensitivity of systems to small climate change (for example, a 1°C warming) or for indicating how soon the effects of global warming may be seen.

To help identify sensitivities and give a sense of when effects may occur, this study uses transient scenarios of climate change. A transient scenario is a scenario of how climate may change over time. For this study, it would be helpful to have a transient scenario starting in current conditions and ending when the equilibrium climate is reached. The options for creating scenarios and the scenarios chosen for this study are discussed in this chapter.

A number of options exist for creating regional scenarios of global warming. These options include the following:

1. arbitrary changes in climate,
2. analogue warming, and
3. use of General Circulation Models.

Arbitrary Changes

A simple way of constructing a scenario is to assume that climate variables change by some arbitrary amount. For example, one could assume that temperature increases by 2 or 4°C, or that rainfall rises or falls by 10%. Such scenarios are relatively easy to use and can help to identify the sensitivities of systems to changes in different variables. To determine how sensitive a system is to temperature alone, one could hold other variables at current climate levels and change temperature by arbitrary amounts.

A major drawback to using scenarios with arbitrary changes is that they may not be realistic, since temperature, evaporation, precipitation, wind, and other variables will most likely change. A combination of unrealistic meteorological changes may yield an unrealistic effect. Scenarios with arbitrary changes may be useful for determining sensitivities to particular variables, but not for determining the possible magnitudes of effects.

Analogue Warming

Many climatologists have advocated the use of historic warming periods as an analogue of how a future warming may affect regional climates (Vinnikov 1987). The instrumental weather record can be used by comparing a cool decade on record, such as the 1880s, with a warm decade, such as the 1930s (Wigley, 1987).

Paleoclimatic data may also be incorporated into an analogue warming scenario. Paleoclimatologists have determined how rainfall and temperature patterns on a broad regional scale differed in the past. The changes associated with past climates that were warmer than now may be used as an analogue warming scenario. For example, 6,000 years ago, the temperatures were about 1°C warmer.

The advantage of using an analogue is that it gives a realistic sense of how regional and local weather patterns change as global climate warms. The 1880s and 1930s daily historic data could be used to determine geographic and variability differences in climate on a local scale.

However, analogues have several drawbacks. First, they are not consistent with the range of global warming now thought likely under the greenhouse effect: 1.5 to 4.5°C. The warmest period of the last 125,000 years was 1°C warmer than the present temperature. In addition, the cause of the past warmings was not only a change in the concentration of greenhouse gases, but also shifts in the Earth's axis, which caused different regional distribution of climate than would be associated with changes in radiative forcing. Second, historic records do not provide enough detail to conduct comprehensive analysis of the 1°C warming. Paleoclimatic records only indicate broad regional patterns of change for a few variables, such as temperature, rainfall, and solar radiation. We can not discern local, daily, or interannual climate from these records. Even using the 1930s presents some problems. Daily records are available only for temperature and rainfall. Some effects models need more variables, such as wind or radiation. Furthermore, the number of weather stations with 1930s data is limited, which could present calibration problems.

General Circulation Models (GCMs)

GCMs are dynamic models that simulate the physical process of the atmosphere and oceans to estimate global climate. These models have been developed over two decades and require extensive computations to run. They can be run to estimate current climates and climates under different compositions of greenhouse gases. The GCMs are often used to simulate climate following a doubling of carbon dioxide levels, otherwise referred to as doubled CO_2. Output is given in regional grid boxes.

The climate change estimated by the GCMs is consistent with the effective doubling of CO_2 concentrations of the atmosphere. The effective doubling of CO_2 means that the combined radiative forcing of the increase in concentrations of all greenhouse gases has the same radiative forcing as doubling CO_2 levels.

The effective doubling of CO_2 concentrations will occur around the year 2030 if current emissions trends continue. The climate change caused by an effective doubling of CO_2 may be delayed by 30-40 years or longer.* Estimates of climate change caused by this effective doubling of CO_2 are referred to as "$2xCO_2$ scenarios."

GCMs have several advantages over the other approaches for creating scenarios. First, the models are used to estimate how global climate may change in response to increased concentrations of greenhouse gases. Thus, regional outputs are consistent with a global warming associated with $2xCO_2$. Second, the estimates of climate variables (for example, rainfall, temperature, and humidity levels) are internally consistent. Third, GCMs estimate outputs for many meteorologic variables (including wind, radiation, cloud cover, and soil moisture) providing enough input for effects models. Fourth, GCMs simulate climate variability, in some cases on a daily basis.

One of the major disadvantages of GCMs is their low spatial resolution. GCMs give outputs in grid boxes that vary in size from 4 by 5° to as much as 8 by 10°. Figure 3-1 shows the grid boxes from the Goddard Institute for Space Studies (GISS) model overlaid on a map of the United States. The grid boxes are 8 by 10° and are larger than the land area of France (Mitchell, 1988). Within each area, the actual climate may be quite variable. For example, the weather in southern Washington State may be quite different from the weather in northern California, but both are in the same grid box. The models, however, do not account for variations within each grid box. Instead, they estimate average climatic conditions for the entire grid box. So, for any

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*This estimate does not account for the effect of the Montreal Protocol on emissions of chlorofluorocarbons (CFCs). If implemented, the protocol will slow the rate of CFC emissions, delaying the date of "effective doubling."

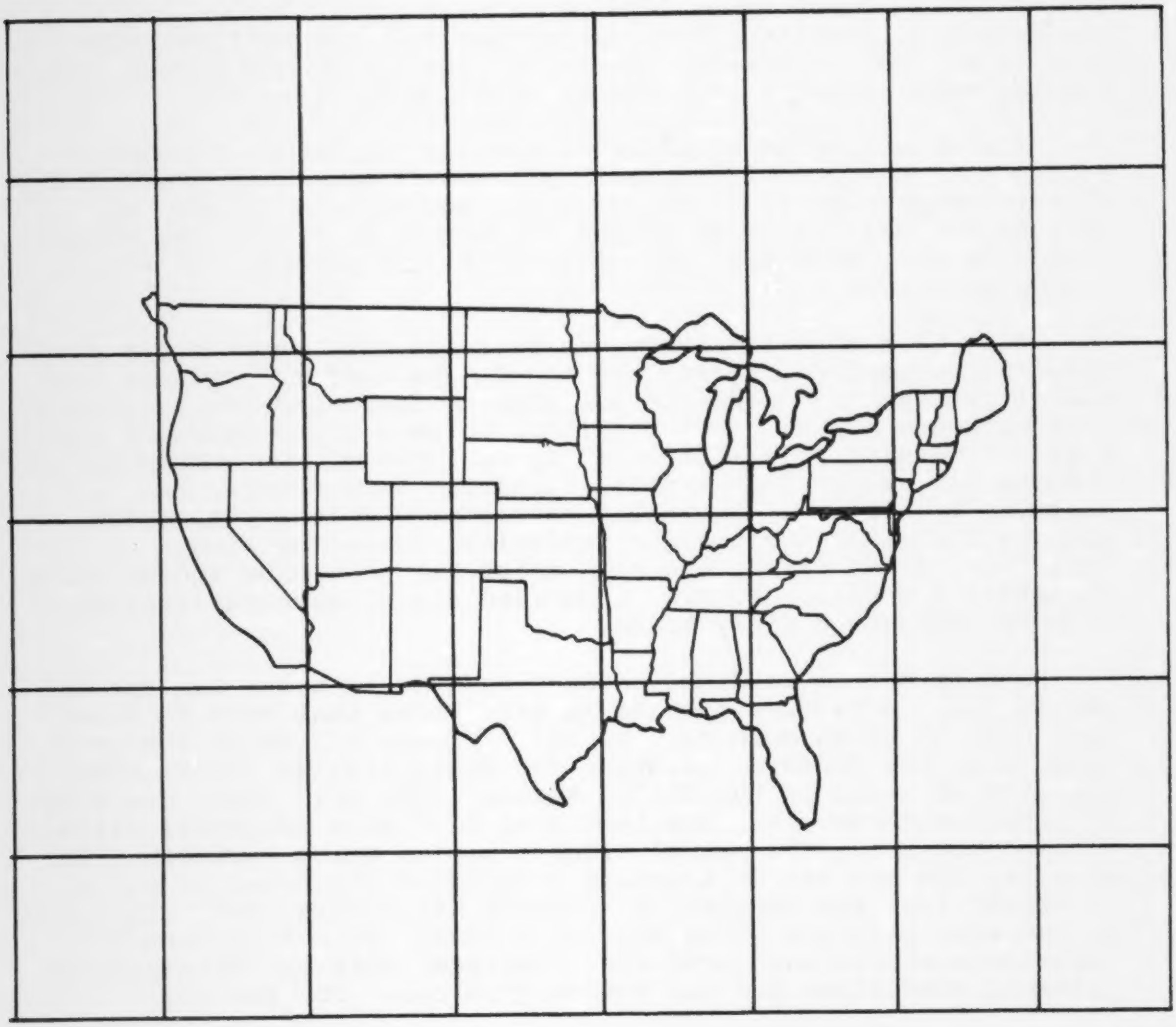


Figure 3-1. GISS Model of the United States.

simulated day, they provide a single value for temperature, for rainfall, and for other variables for the entire area of the box.

A second disadvantage is that the models do not satisfactorily simulate the oceans, which lowers confidence in the GCMs' ability to simulate regional climate and climate variability. GCMs disagree on regional climate, with two models often showing opposite changes in some variables (such as precipitation) for the same location. (Model disagreement on regional climate change is the subject of a recent study by Grotch, 1988.) A low level of confidence also exists regarding model estimates of variability, on both a daily and an interannual basis. (See the Climate Variability chapter of this report for a discussion of GCM estimates regarding changes in variability.) In sum, a relatively greater degree of confidence exists regarding estimates of average and global climate changes than regarding regional climate and variability estimates.

Choice of 2xCO_2 Scenario

GCM outputs are employed as a basis for constructing the scenarios to be used in our report because they produce regional climate estimates consistent with doubled CO_2 concentrations. Yet, GCMs are relatively new tools that need a great degree of refinement. Their results must be applied with caution. A conservative approach requires using only the outputs from the GCMs for which the atmospheric modelers have expressed the greatest confidence, specifically the average monthly changes in each grid box.

The scenarios described in this chapter are a hybrid between GCM outputs and historic weather data. The estimates of average monthly change in temperature, precipitation, and other weather variables are used in a grid box from the GCMs. Model simulations of current conditions are compared with simulations of 2xCO_2 conditions. The ratios of (2xCO_2)/(1xCO_2) are multiplied by historic weather conditions at weather stations in a grid box. Parry et al. (1987) used this approach in an analysis of impacts of climate change on agriculture. Thus, if a grid box is 2°C warmer under the GCM scenario, all stations in that grid are assumed to be 2°C warmer. The effect of this is to keep variation from station to station within a grid the same as in the historic base period. Furthermore, interannual and daily variability remain the same. If it rains 10 days in a month, in the scenario it also rains 10 days in the month, and the amount of rainfall is adjusted by the GCM output.

The years 1951-80 were chosen as the base period to which average $2xCO_2$ changes were applied. Several decades of data allow for a great deal of interannual variability, giving a wide range of warm, cold, wet, and dry years. Since the data are from the most recent decades, they are the most complete historic data available.

GCMs Used

To obtain a range of scenarios, output from three GCMs is used:

- Goddard Institute for Space Studies (GISS) (Hansen et al., 1988),
- Geophysical Fluid Dynamics Laboratory (GFDL) (Wetherald and Manabe 1988), and
- Oregon State University (OSU) (Schlesinger and Zhao, 1988).

The average seasonal temperature and precipitation for the United States gridpoints for each model are displayed in Figure 3.2. All three models yield an average warming over the United States, with OSU giving 3°C, GISS 4.3°C, and GFDL 5.1°C. The seasonal patterns are different, with GISS having a larger warming in winter and fall, GFDL having the highest temperature change in the spring, and OSU having little seasonal variability. All three models estimate that annual precipitation would increase. GISS and OSU estimate that annual precipitation would rise by respectively, 73 mm (2.92 inches) and 62 mm (2.48 inches), while GFDL has a rainfall increase of only 33 mm (1.31 inches). The first two models have precipitation increases in all four seasons, while GFDL has a summer decline in rainfall. In sum, OSU appears to be the "mildest" scenario, with the lowest temperature rise and largest increase in precipitation. GFDL appears to be the most "extreme," with the highest temperature rise, the smallest increase in precipitation, and a summer decrease in rainfall.

Limitations

A major limitation of the $2xCO_2$ scenarios used for this study is the lack of temporal and spatial variability. By applying average monthly changes to the historic data set, it is assumed that the daily and interannual patterns of climate remain the same. This assumption is probably unrealistic, since a change in average conditions will probably lead to a change in

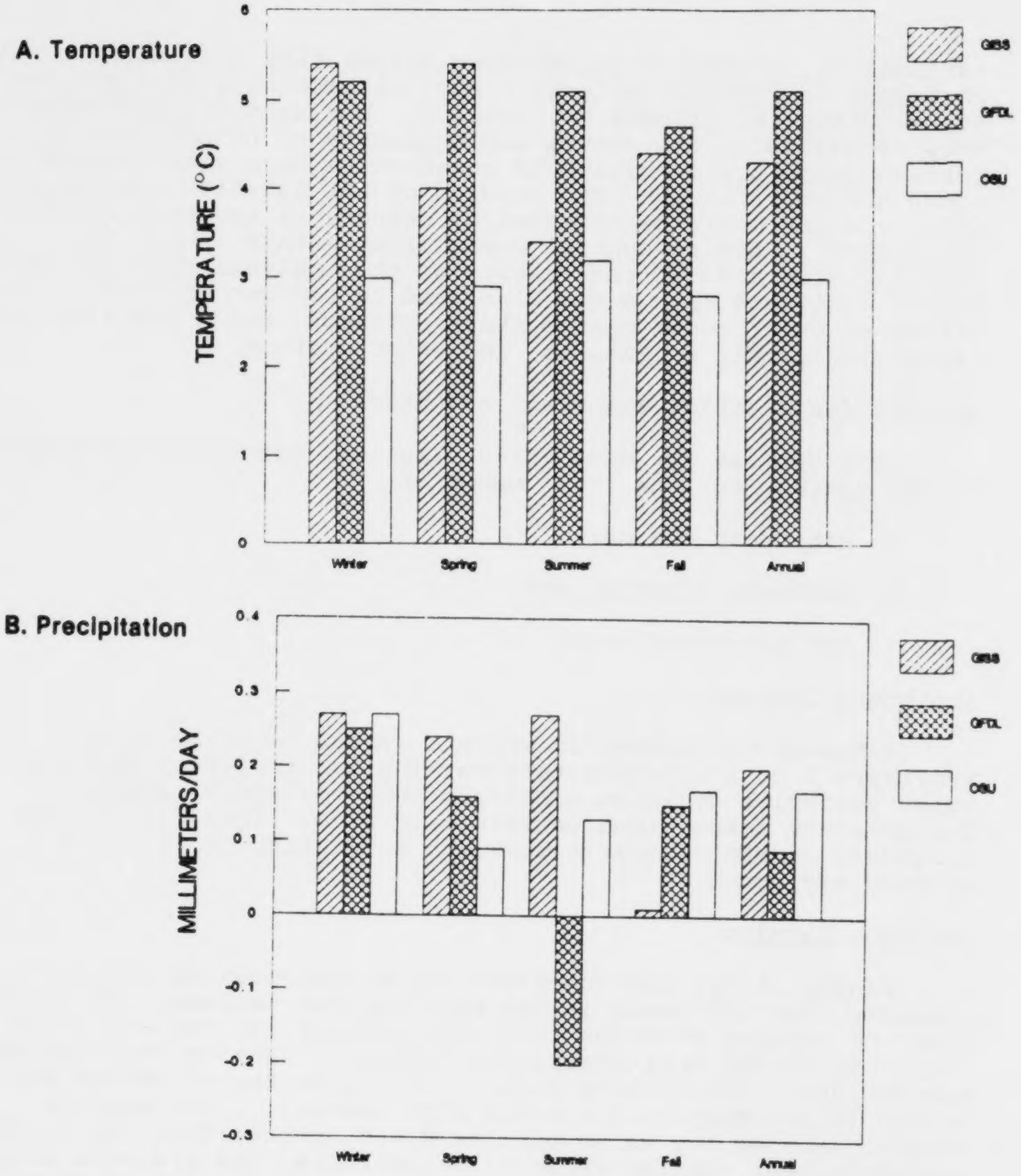


Figure 3-2. Average changes in temperature (°C) and precipitation (mm/day) over lower 48 States grid boxes.

variability. Furthermore, holding variability constant can have an impact on effects analysis. Most climate-sensitive systems are sensitive to climate variability. For example, riverflow is very sensitive to the amount and intensity of rainstorms. Certain crops are sensitive to consecutive days with temperatures above a certain level. The studies do not identify how these and other systems could be affected by changes in temporal climate variability. Holding spatial variability within a grid box constant also affects the results of the analyses done for this report. Climate change may also lead to changes in wind patterns, which could change storm patterns, cloud distribution, deposition of air pollutants, and other systems.

Options for Creating Transient Scenarios

The options for developing transient scenarios are similar to the options for the $2xCO_2$ scenarios:

1. arbitrary changes,

2. analogue warming, and

3. GCM transient runs.

Arbitrary Changes

Although the manner in which a system responds to an arbitrary 1 or 2°C temperature warming and arbitrary changes in other variables could be examined, the problems of physical inconsistent assumptions pertain here also. In addition, the arbitrary warming scenario gives no indication of when the warming may occur.

Analogue Warming

Wigley (1987) has suggested using analogues as scenarios for climates that may occur in the next several decades. He notes that the warming from the late 19th century to 1940 was about 0.4°C, which may approximate the transient warming over the next two decades. The problem here is that climate may change faster in the future than in the early 20th century. (The average decadal warming may be as much as 0.5°C, rather than the 0.1°C identified for earlier years.) Furthermore, the analogue only takes one as far as a 0.5°C -- or in the case of paleoclimatic records, a 1°C -- warming. It does not indicate what happens in decades after the 0.5-1.0°C level is reached. In addition, the analogue may not represent the regional distribution of climate associated with greenhouse forcing.

GCM Transient Run

GISS has modeled how global climate may change as concentrations of greenhouse gases gradually rise over the next century. This is called the transient run. GISS has modeled climate change under several assumptions of trace gas growth. The transient runs start in 1958 with the atmospheric concentrations of greenhouse gases that existed at that time. The concentrations of the gases and equivalent radiative forcing are then increased from 1958 until an arbitrary point in the future according to assumptions regarding trace gas growth. The GISS transient run yields daily climate estimates from 1958 until that arbitrary point.

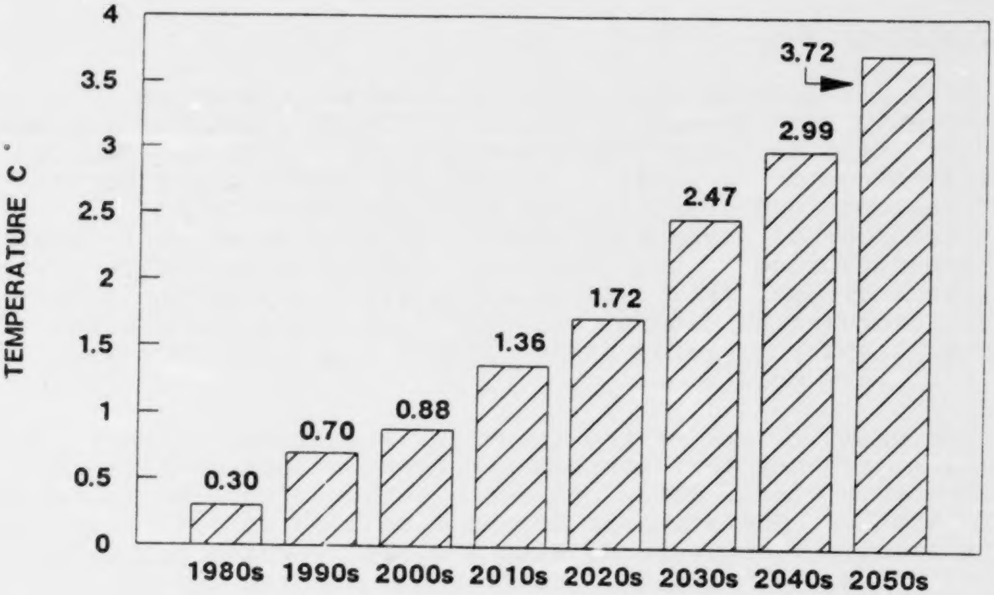
For example, one of the transient scenarios, which is known as GISS A, assumes that trace gas concentrations continue to increase at historic rates and net greenhouse forcing increases exponentially. The scenario is run from 1958 to 2062. The end of the transient corresponds with a global warming equivalent to that of the equilibrium climate from the doubled CO_2 run. GISS B assumes a decreasing trace gas concentration growth rate such that the annual increase in climate forcing stays the same (Hansen et al., 1988). GISS B stops in 2029.

Since the GCMs are used to produce this transient run, the advantages and disadvantage of using this approach are the same as those described in the discussion of doubled CO_2 scenarios. In addition, the timing of the changes estimated by the GCMs is complicated by the uncertainties regarding the growth of greenhouse gas emissions and the roles of the oceans and clouds in delaying climate changes.

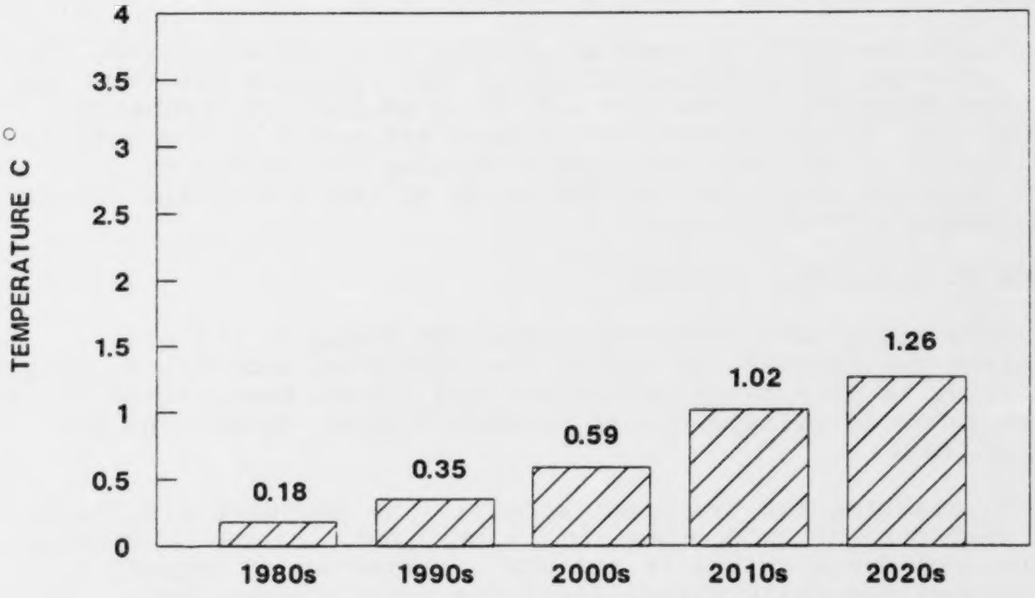
Choice of Transient Scenario

This study uses transient scenarios based on the GISS transient run because, of all of the different approaches, only this study is internally consistent and allows examination of the entire range of climate change between current conditions and $2xCO_2$ climate.

In creating the transient scenario, an approach similar to that used for the $2xCO_2$ scenario is employed. Since relatively little confidence exists in the GCM's estimates of changes in interannual and daily variability, the monthly means are calculated for each decade of the transient. This process gives average decadal temperature, precipitation, and other changes. The average decadal temperature changes in GISS A and B for the United States are shown in Figure 3-3.



TRANSIENT SCENARIO A



TRANSIENT SCENARIO B

Figure 3-3. GISS transients "A" and "B" average temperature change for lower 48 States grid points

As in the $2xCO_2$ scenario, the average meteorologic changes from the transient are combined with a historic time series. What is different from the $2xCO_2$ scenario is that a gradual change in temperature and other variables is mixed with a historic time series with its own variability. This can produce a "sawtooth" effect.

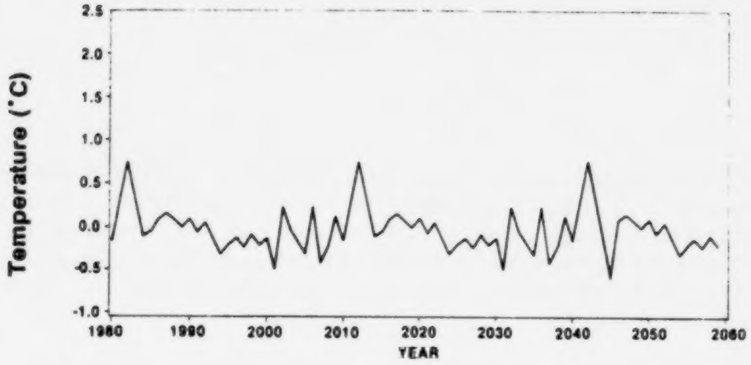
In this study, the historic time series 1951-80 is used, and the transient monthly statistics are applied to the time series. The procedure for creating the transient scenario is to first linearly interpolate between decadal means. This smoothes out sharp decadal changes from the transient GCM results. The monthly underlying climatic change, starting with the decade of the 1980s in the GISS run to the actual 1950s data, is then added. The statistics from the 1990s in the GISS run are added to the 1960s, and those from the 2000s are added to the 1970s. Then, the monthly averages from the 2010s are combined with 1950s actual data, and so on, until the end of the transient is reached. Although there is a cooling from the 1950s to the 1960s, followed by a warming in the 1970s, the underlying warming of the transient, which is 3.7°C by the middle of the 2050s in GISS A, is much greater than the variability in the base period. This is shown in Figure 3-4, which displays the smoothed decadal averages from GISS A, the 1951-80 decadal averages for the United States, and the combination of the two to create one of the transient scenarios.

Limitations

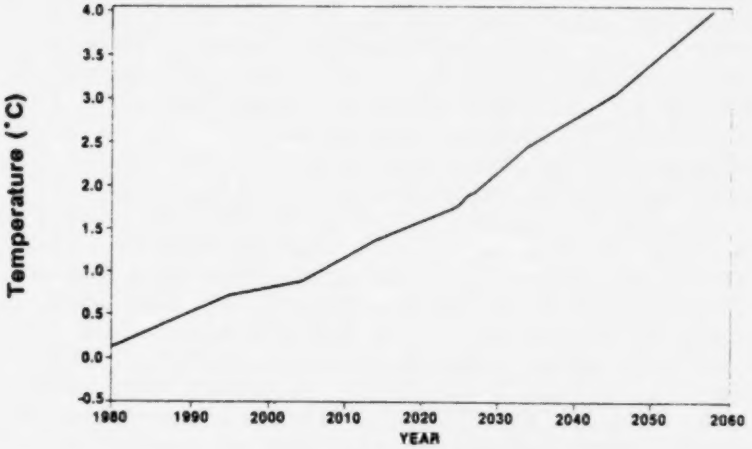
Since the transient scenarios are also derived from GCMs, the same limitations concerning temporal and spatial variability pertain as in the $2xCO_2$ scenario. An additional limitation in the transient scenario is the rate of change. The GISS transient runs assume a gradual rate of change in temperature. This is complicated by the addition of the 1951-80 base period, which yields short-term oscillations and a sawtooth effect. Broecker (1987) has shown that past climatic changes may have been abrupt. A sudden warming could mean that significant effects happen sooner and more suddenly than the results of the transient analysis used in this study indicate.

Other Scenarios

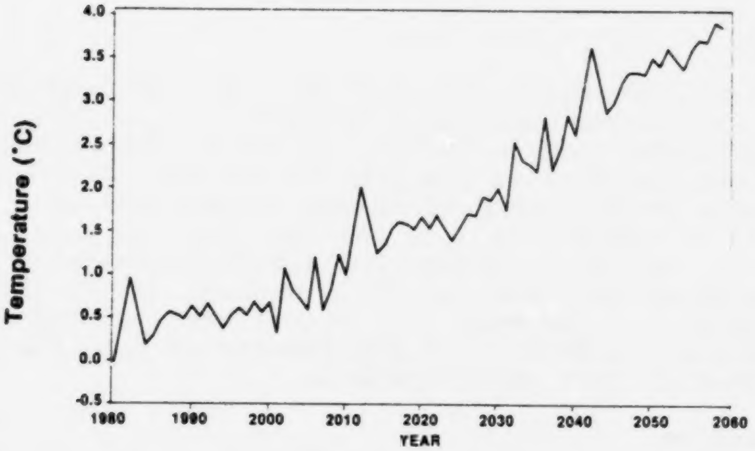
In a few cases, researchers used meteorologic data from the 1930s as an analogue scenario. This scenario was used to provide additional information on the sensitivity of systems to climate change. In a few other cases, researchers only examined



A. 1951 - 1980



B. SMOOTHED GISS "A"



C. TRANSIENT SCENARIO, SMOOTHED GISS "A"
AND 1951 - 1980 REPEATED

Figure 3-4. Transient scenarios.

paleoclimatic records. In these cases, the goal was to determine how a system responded to past climate change.

Unlike the climate scenarios, the alternative sea level rise scenarios were not based solely on the differences between various general circulation models. Instead, they were based on the range of estimates that previous studies have projected for the year 2100. (Hoffman et al. 1983, 1986; Meier et al. 1985; Revelle 1983; Thomas 1986) which have generally considered alternative rates of greenhouse gas emissions, climate sensitivity ranging from 1.5 to 4.5°C for a CO_2 doubling; and uncertainties regarding ocean expansion and glacial melting. Estimates for the year 2100 generally range from 50-200cm.

This report uses three scenarios for the year 2100: 50, 100, and 200 cm, the current trend of 12 cm/century. Because most studies have not reported estimates for the intermediate years, we followed the convention of a recent NRC report (Dean et al.) and interpolated sea level rise using a parabola, as illustrated in figure 3-0. Because various coastal areas are also sinking (and in a few cases rising), relative sea level rise at specific locations was estimated by adding current local subsidence trends.

EFFECTS ANALYSES

In this study, the preferred approach for analyzing potential impacts of climate change was to develop quantitative estimates. Most researchers estimated impacts by running models that simulate the relationship of weather and the relevant system. The climate scenarios were used as inputs into the models. Since the researchers only had several months to do the analysis, they either used "off-the-shelf" models or analytic techniques. In many cases, existing models were calibrated to new sites. This lack of time also limited the gathering of new data to a few studies.

A drawback of using quantitative models of systems to estimate sensitivities is that the models are applied to climates for which they were not developed. The models estimate relationships between weather on record and the system. This relationship is then extrapolated to an unprecedented climate. It is possible that in the new climate situation, the statistical relationship may be different due to crossing of a threshold or some other reason. With the drawbacks of quantitative models, the current statistical relationships are the best basis for quantitatively estimating sensitivities.

For the most part, researchers analyzed the potential effects of climate change on systems as they currently exist. Although these changes may be quite substantial, potential changes in populations, GNP, technology, and other factors were not considered. In some cases, researchers ran additional scenarios with assumptions about technological and other changes. In addition, potential responses to climate change were considered in some, but not all, cases. For these and many other reasons, the results should only be interpreted as indicative of the sensitivity of current systems to climate, not as a prediction of what the effects will be.

In some situations, quantitative models of the relationship between climate and a particular system did not exist. In those cases, other approaches were used to try to identify sensitivities. Some researchers examined how systems responded to analogue warmings. In other cases, expert judgment was used. This consisted of literature reviews to assemble information on sensitivities as they appear in the literature, and workshops and interviews to poll experts on how they thought systems would respond to global warming.

REFERENCES

Broecker, W.S. 1987. Unpleasant surprises in the greenhouse? Nature 328:123-126.

Grotch, S.L. 1988. Regional Intercomparisons of General Circulation Model Predictions and Historical Climate Data. Prepared for United States Department of Energy. TR041.

Hansen, J., I. Fung, A. Lacis, D. Rind, G. Russell, S. Lebedeff, R. Ruedy, and P. Stone. 1988. Global climate changes as forecast by the GISS 3-D model. Journal of Geophysical Research (In press.)

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis. 1983. Efficient three-dimensional global models for climate studies: models I and II. Monthly Weather Review 3(4):609-622.

Hoffman, J.S., D. Keyes, and J.G. Titus. 1983. Projecting future sea level rise. Washington, DC: Government Printing Office.

Hoffman, J.S., J. Wells, and J.G. Titus. 1986. Future global warming and sea level rise. In Iceland coastal and river symposium. ed. G. Sigbjarnarson. Regkjavid/Iceland: National Energy Authority

Meier, M.F., et al. 1985. Glaciers, ice sheets, and sea level. Washington, D.C.: National Academy Press.

Mitchell, J.F.B. 1988. Local effects of greenhouse gases. Nature 332:399-400.

Parry, M., T. Carter, N. Konijin, and J. Lockwood et al. 1987. The Impact of Climatic Variations on Agriculture: Introduction to the IIASA/UNEP Case Studies in Semi-Arid Regions. International Institute for Applied Systems Analysis.

Revelle, R. 1983. Probable future changes in sea level resulting from increased atmospheric carbon dioxide. In Changing Climate. Washington, DC: National Academy Press.

Schlesinger, M. and Z. Zhao. 1988. "Seasonal Climate Changes Induced by Doubled CO_2 or Simulated by the OSU Atmospheric GCM/Mixed-Layer Ocean Model" Oregon State University Climate Research Institute Report. Carvallis, Oregon.

Thomas, R.H. 1986. In Titus, J.G. 1986. Effects of changes in stratosphere ozone and global climate. EPA and UNEP: Washington, DC.

Vinnikov, K.Y., and N.A. Lemeshko. 1987. Soil Moisture Content and Runoff in the USSR Territory With Global Warming. Journal of Meteorology and Hydrology No. 12.

Wetherald R.T. and S. Manabe. 1988. "Cloud Feedback Process in a GCM" Journal of Atmospheric Sciences. April, 1988

Wigley, T.M.L. 1987. Climate Scenarios. Prepared for the European Workshop in Interrelated Bioclimate and Land-Use Changes. National Center for Atmospheric Research. NCAR 3142-86/3.

DRAFT

CHAPTER 4

POTENTIAL IMPACTS OF CLIMATIC WARMING ON CALIFORNIA

FINDINGS

Global warming could cause higher winter and lower spring runoff in California and increasing the difficulty of meeting water supply needs. It could also increase the salinity in San Francisco Bay and the Delta and the relative abundance of marine species in the Bay; degrade water quality in alpine lakes; raise ambient ozone levels; and increase electricity demand. Changes in agriculture are uncertain.

Water Resources

- Higher temperatures would lead to higher winter runoff from the mountains surrounding the Central Valley, because less precipitation would fall as snow, and the snowpack would melt earlier. Runoff in the late spring and summer would consequently be reduced.

- As a result, the amount and reliability of water supply from reservoirs in the Central Valley basin would decrease. Annual water deliveries from the State Water Project could be reduced by 7 to 16 percent. Even if operating rules are changed, current reservoirs would not have the capacity to store the heavier winter runoff and at the same time retain flood control capabilities.

- The water area and volume of the San Francisco Bay estuary could increase due to a one-meter (40-inch) sea level rise. If the Delta and Bay levees are maintained, the increase in area and volume would be, respectively, 300 km^2 and 1.2 billion m^3 (about 30 and 15 percent). If the levees fail, the area and volume would, respectively, triple and double, an increase of 2,400 km^2 and 6.8 billion m^3.

- Saline (brackish) water might migrate inland between 4 km (2.5 miles) and 10 km (6 miles) if sea level rises 1 meter, if the levees fail, and if there is no erosion of tidal channels. Freshwater releases into the Delta might have to be doubled in order to repel saline water near the major freshwater pumping facilities.

Wetlands and Fisheries

- The wetlands in San Francisco Bay estuary will gradually be inundated as sea level rises. The amount of wetland lost will be a function of the rate of sea level rise and whether shorelines are protected. If sea level rises 1 meter by 2100, the rate of rise will be greater than wetland vertical accretion by the middle of the next century. If sea level rises 2 to 3 meters by 2100, wetlands will start to be inundated early in the next century.

- If salinity increases within the San Francisco Bay estuary, wetland vegetation will shift from brackish and freshwater species to more salt-tolerant plants. This shift could severely reduce waterfowl populations that depend on freshwater habitats. The timing, magnitude, and location of phytoplankton production would shift. Marine fish species could increase in abundance, while saltwater species that breed in freshwater areas would most likely decline.

- Higher temperatures in subalpine lakes could increase annual primary production (such as algae) by between 16 percent and 87 percent, which could degrade lake water quality and change the composition of fish species.

Agriculture

- The impacts of climate change on agriculture in California are uncertain. The effects of changes in temperature and precipitation alone would most likely reduce yields 4 to 40 percent, depending on the crop. However, with the combined effects of climate and higher CO_2 levels, yields for all crops, except corn, might increase.

- The potential growth in irrigation in some parts of the state may require increased extraction of groundwater due to current full use of surface water supplies. This would decrease water quality and affect water management options.

- Yields in California may be less than in most parts of the country. Crop acreage could increase because of the shifts in yields and the presence of irrigation infrastructure.

Natural Vegetation

- Drier climate conditions could reduce forest density, particularly pine and fir trees, and timber productivity.

(The full impacts on California forests was not assessed in this report).

Air Quality

- If today's emissions exist in a future warmer climate, Ozone levels in the San Francisco Bay will intensify and will change location due to higher temperatures. As a result, the number of people hours exposed to elevated ozone levels in excess of EPA standards (of 0.12 pphm) would triple.

Electricity Demand

- The annual demand for electricity in northern California could rise by 3 to 6 billion kilowatt hours (1 to 2 percent) by 2010 and by 21 to 41 BKWH (3 to 5 percent) by 2055.
- By 2010, 2-3 gigawatts (GW) would be needed to meet the increased demand. By 2055, 10-20 GW would be needed -- a 10 to 20 percent increase over baseline additions that may occur without climate change. The additional capital cost by 2055 would be $10 to 27 billion.

Policy Implications

- Water management institutions, such as the U.S. Bureau of Reclamation and the California Department of Water Resources, should analyze the potential impacts of climate change on water management in California. They should consider whether and how the Central Valley Project and State Water Project should be modified to meet diminishing supplies and increasing demands due to climate change. They may also consider whether to change water allocation rules to encourage more efficient use of water.
- State and local entities should consider the impacts of climate change on levee management in San Francisco Bay and the Delta.
- The California Air Quality Board should review the long-term implication of climate change on air quality management strategies.
- The California Energy Commission should consider the impacts of climate change on the energy supply needs for the State.

CLIMATE SENSITIVE RESOURCES OF CALIFORNIA

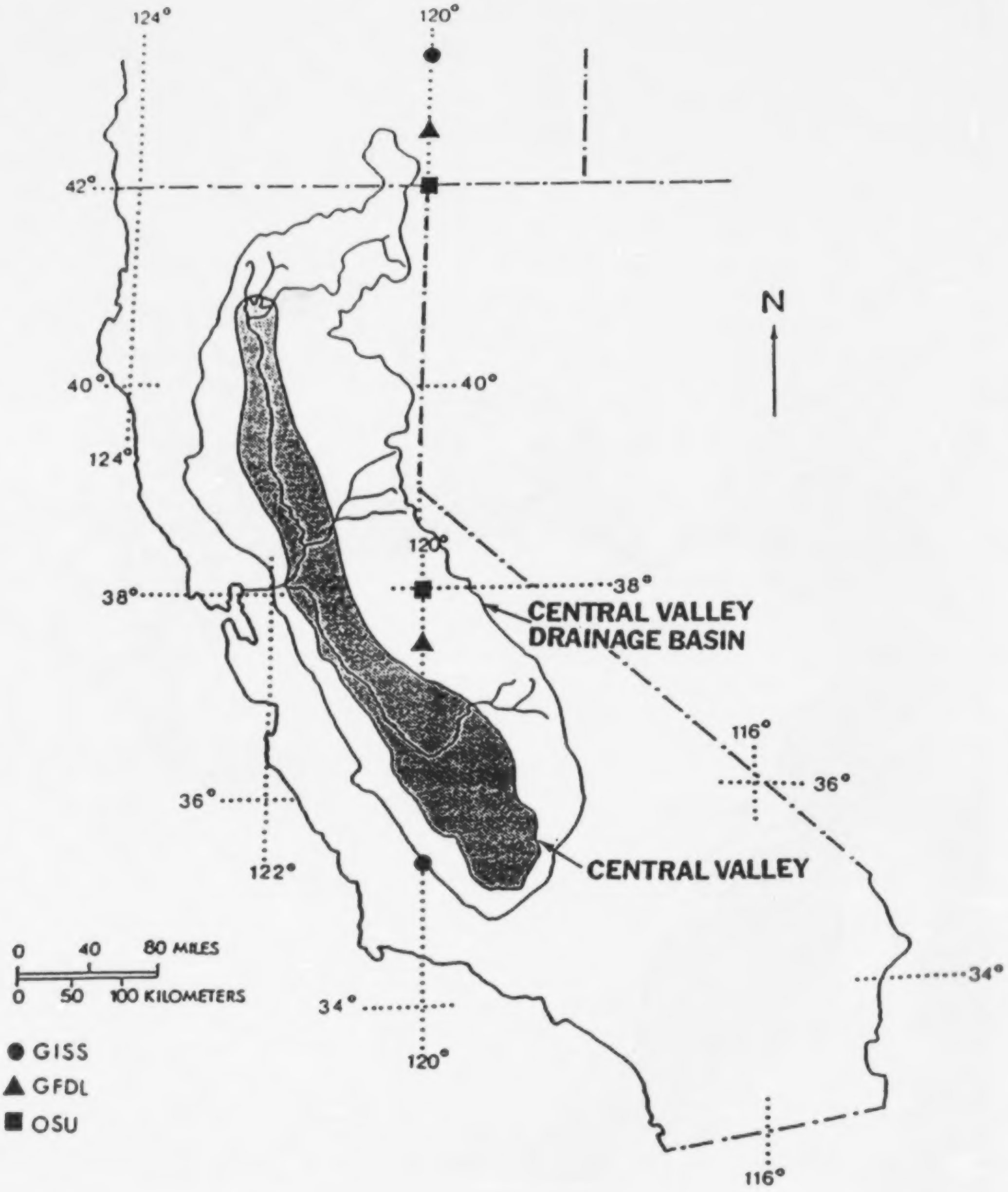
California's Central Valley is the most productive and diverse agricultural region of its size in the world. The Central Valley Basin, which includes the drainages of the Sacramento and San Joaquin Rivers, encompasses several large metropolitan areas, dispersed manufacturing, major port facilities, important timber reserves, heavily used recreational areas, and diverse ecosystems.

Much of the region's economic and social importance is derived from its water resources. Over 40% of California's total surface water runoff drains from the Central Valley Basin into the San Francisco Bay area (Miller and Hyslop, 1983). The basin supplies water for irrigated agricultural, municipal, and industrial uses, and for a host of other resources and activities.

The Central Valley Basin encompasses approximately 40% of California's land area (Figure 4-1). Elevations range from just below sea level on leveed islands in the Sacramento-San Joaquin River Delta to peaks of over 4,200 m (14,000 feet) in the Sierra Nevada (Figure 4-2). Mountains ring most of the basin: the Sierra Nevada along the eastern side and the Coast Ranges on the west. The only outlet to the Pacific Ocean is through the San Francisco Bay estuary (Figure 4-2).

Current Climate

California's climate is characterized by little, if any, summer precipitation, and winters are generally wet (Major, 1977). Temperature and precipitation vary with elevation and latitude in the Central Valley basin. Extremes in mean annual precipitation range from about 15 cm (6 inches) in the southern San Joaquin River Basin to about 190 cm (75 inches) in the mountains of the Sacramento River Basin. While almost all valley floor precipitation falls as rain, winter precipitation in the high mountains often falls as snow. Storage of water in the snowpack controls the seasonal timing of runoff in the Central Valley rivers and has shaped the evolution of strategies for water management and flood protection. Under current climatic conditions, peak runoff occurs between February and May for individual rivers within the Central Valley Basin (California Department of Water Resources, 1983; Gleick, 1987b).


124°
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0 40 80 MILES
0 50 100 KILOMETERS
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34°
120°
● GISS
▲ GFDL
■ OSU
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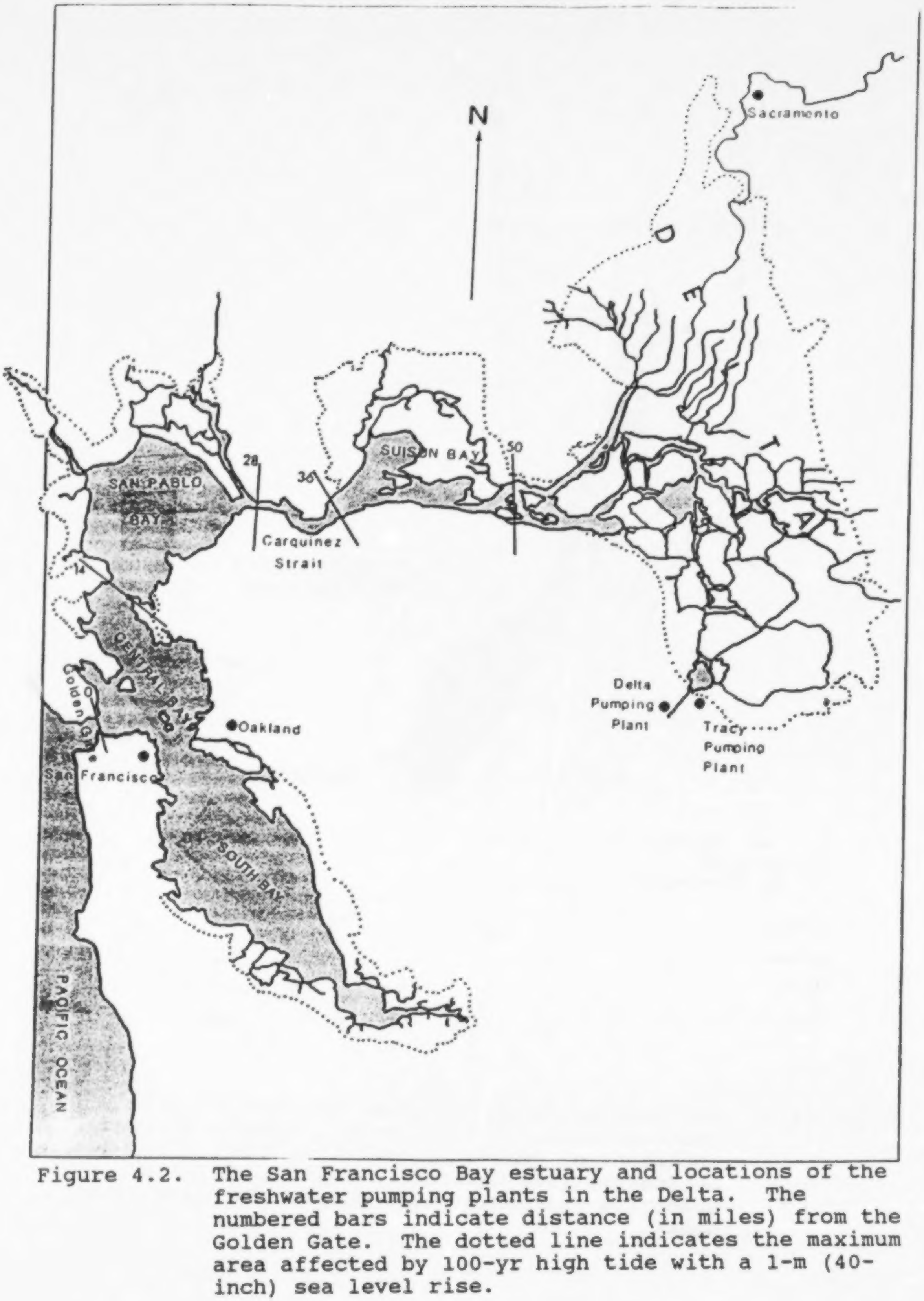
Figure 4.1. The Central Valley (shaded) and Central Valley Drainage Basin of California. Symbols refer to locations of General Circulation Model (GCM) gridpoints (see California Regional Climate Scenarios section of this chapter for details on GCMs).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CENTRAL BAY
Golden Gate
0
Oakland
San Francisco
SOUTH BAY
PACIFIC OCEAN
Delta
Pumping
Plant
Tracy
Pumping
Plant

Figure 4.2. The San Francisco Bay estuary and locations of the freshwater pumping plants in the Delta. The numbered bars indicate distance (in miles) from the Golden Gate. The dotted line indicates the maximum area affected by 100-yr high tide with a 1-m (40-inch) sea level rise.

Water Resources

Water Distribution

California's water resources are poorly distributed, relative to human settlement patterns in the State. Over two-thirds of the State's surface water supply originates north of Sacramento, and 70% of its population and 80% of its total demand for water lie to the south (California Department of Water Resources, 1985). In addition, about 85% of the Central Valley Basin's total annual precipitation occurs between November and April, whereas peak water use occurs during the summer.

In working to solve these water distribution problems, the U.S. Government and California have built two of the largest and most elaborate water development projects in the world: the Federal Central Valley Project (CVP) and the California State Water Project (SWP). Both are essentially designed to move water from water-rich northern California to the water-poor south, and to supply water for agriculture and municipal and industrial purposes. Currently, the CVP has a surplus of water and the SWP has a shortage, especially in relationship to users' projected requirements. Thus, the SWP is particularly susceptible to dry years.

Flood Control and Hydroelectric Power

Another objective of the CVP and SWP is flood control. By 1984, CVP facilities had prevented almost $500 million in flood damages (U.S. Bureau of Reclamation, 1985). Flood control, however, comes at the expense of water storage (and hence water deliveries), because reservoir levels must be kept low to absorb high river flows. A warmer climate could increase the severity of winter floods by reducing the proportion of total precipitation falling as snow in the Sierra Nevada during a given storm. Controlling these floods could reduce water deliveries.

Hydroelectric power generation is also an objective of the CVP and SWP, and surplus power is sold to utility companies. CVP powerplants produce an average of 5.5-6 billion kilowatt-hours (kWh) per year. In 1976 and 1977, precipitation was 35 and 55% below normal, respectively, and hydroelectric power generation fell to 50 and 40%, respectively, of target production.

Sacramento and San Joaquin River Delta

The delta at the confluence of the Sacramento and San Joaquin Rivers is the focal point of major water-related issues in

California. For example, many islands in the delta lie below sea level and are protected by levees, some of which are made of peat and are relatively fragile. These islands would be vulnerable to inundation from rising sea level associated with climatic warming. The deep peat soils on these islands support highly productive agriculture that would be eliminated under inundated areas.

In addition to agricultural importance, the delta is also the source of all CVP and SWP water exports to points farther south. The freshwater pumping plants (see Figure 4-2) in the delta are the two largest single freshwater diversions in California (Sudman, 1987). Delta outflow must be maintained at a required level to prevent saltwater intrusion into the pumping plants (see Figure 4-2). The volume of water released from upstream reservoirs to achieve this is called carriage water. Higher sea levels could exacerbate the existing problem of saltwater intrusion and require the release of greater volumes of carriage water.

Commerce

The San Francisco Bay estuary includes the largest bay on the California coast (see Figure 4-2). The bay's northern reach between the Golden Gate and the Sacramento-San Joaquin River Delta is a brackish estuary dominated by seasonally varying river inflow (Conomos et al., 1985). The southern reach between the Golden Gate and the southern terminus of the bay is a tidally oscillating lagoon-type estuary. The port facilities of the San Francisco Bay area are vital to California's internal trade, to Pacific Coast commerce, and to foreign trade, particularly with Asian countries. The ports of Oakland and San Francisco, combined, ranked fourth in the United States in tonnage of containerized cargo handled in 1983 (U.S. Maritime Administration, 1985). These facilities and operations are sensitive, in varying degrees, to both sea level change and fluctuation in freshwater runoff. For example, an increase in sea level could make navigation easier, reducing the need for dredging of navigation channels. On the other hand, a rising sea level could threaten fixed port terminals and piers.

Agriculture

California annually produces about 10% of cash farm receipts in the United States with $14.5 billion in farm income in 1986 (U.S. Department of Agriculture, 1987). Central Valley farms make up significant proportions of total U.S. production of many crops, including cotton, apricots, grapes, almonds, tomatoes, and lettuce. Since virtually all Central Valley agricultural production requires irrigation, climatic change effects on water availability and water quality could significantly affect California agriculture.

Agriculture, the primary land use and the largest consumer of water in the Central Valley Basin, accounts for 87% of total net water use in the region. Furthermore, the region accounts for 72% of total net water use for the entire State and almost 80% of net agricultural use (California Department of Water Resources, 1987a).

Forestry

Silviculture is extensively practiced in California's mountains. The nine National forests substantially within the Central Valley Basin recorded over $88.6 million in timber sales in fiscal year 1986 (U.S. Department of the Interior, 1986). Climatic change could harm timber production in the region. For example, the drought of 1976-77 contributed to significant tree mortality because of large infestations of bark beetles (California Division of Forestry and Fire Protection, 1988).

Natural Vegetation

Approximately one-fourth of all the threatened and endangered plants in the United States are found in California. About 460 species, or about 9% of the California species listed by Munz and Keck (1959), are either extinct or in danger of becoming extinct.

California contains about 5,060 native vascular plant species; of these, about 30% occur only in California (Munz and Keck, 1959; Raven, 1977). These species are more numerous than those present in the entire central and northeastern United States and adjacent Canada, a region about eight times larger than California (Fernald, 1950).

Within the Central Valley Basin, terrestrial vegetation may be grouped into the following broad classes, listed according to decreasing elevation: alpine, subalpine forest, montane forest, mixed evergreen forest, chaparral and oak woodland, and valley grassland (Barbour and Major, 1977).

Wetlands

The San Francisco Bay estuary includes approximately 90% of the salt marsh area in California (Macdonald, 1977). Nichols and

Wright (1971) documented a 60% reduction in San Francisco Bay marsh between 1850 and 1968. This reduction was largely the result of reclamation for salt ponds, agriculture, expanding urbanization, shipping facilities, and marinas. Further loss of wetlands from climate change and rising sea level could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry valued at over $150 million annually (Meyer, 1987). Tourism, rare and endangered species, and heritage values also could be harmed.

Wildlife and Fisheries

San Francisco Bay estuary provides vital habitat for many sport and commercial fish species (California Department of Water Resources, 1983). Important sport fish include striped bass, chinook salmon, sturgeon, American shad, and steelhead rainbow trout. These species are anadromous (i.e., saltwater species that enter freshwater areas for breeding) and the delta is an important nursery for these species. Chinook salmon is also an important commercial fish species, and Central Valley rivers support about 75% of California's chinook salmon catch, valued at $13.4 million at 1981 prices. The populations of these species are affected by water quality in the estuary.

In order to protect aquatic organisms in the delta the State Water Resources Control Board (SWRCB) adopted the water right Decision 1485 in 1978 that sets water quality standards to protect the delta and Suisun Marsh. The standards vary year to year, with less stringent requirements in dry years. The standards are met by meeting minimum delta outflow requirements. If delta outflow falls below the required level, then releases from upstream state and federal reservoirs must be increased so the outflow requirement is met. The water quality standards take precedence over water export from the delta.

Recreation and Nature Preservation

Recreation and nature preservation have expanded in recent years. Important recreational areas in the Central Valley Basin include four National parks (Lassen Volcanic, Sequoia, Kings Canyon, and Yosemite) and nine National forests that lie either completely or largely within its boundaries. Two National recreation areas and 13 designated wildlife refuges and management areas also are situated in the region. Downhill skiing and other winter sports are important economically in the State. Water projects throughout the Central Valley Basin provide significant recreational opportunities.

Chapter 4

PREVIOUS CLIMATE CHANGE STUDIES

Two of the few previous studies undertaken to assess the potential effects of climatic change on the region are discussed here.

Forests

Leverenz and Lev (1987) estimated the potential range changes, caused by CO_2-induced climatic change, for six major commercial tree species in the western United States. Two of the species, ponderosa pine and Douglas-fir, have significant populations in California. Leverenz and Lev based their estimates of range changes on the species' response to increased temperature, decreased water balance, and higher CO_2 concentrations. The scenario of climate change used was based on a simulation using the Geophysical Fluid Dynamics Laboratory (GFDL) model (a different run than used for this study), with CO_2 concentrations double their present levels. Their results suggest that in California, ponderosa pine could increase in range and abundance because of its ability to withstand long summer drought. Douglas-fir could be eliminated from coastal lowlands in California but might occur in the coastal area at higher elevations.

Water Resources

Gleick (1987a,b) applied 18 General Circulation Model (GCM)-based and hypothetical scenarios of climatic change to a hydrologic model of the Sacramento River Basin and used a two-part water balance model to estimate the monthly runoff and soil changes in the basin. Application of the scenarios to his model indicates that winter runoff could increase substantially, and summer runoff might decrease under most of the scenarios. Summer soil-moisture levels might also decrease substantially. These changes are driven by higher temperatures which decrease the amount of winter precipitation falling as snow and cause an earlier and faster melting of the snowpack that does form.

CALIFORNIA STUDIES IN THIS REPORT

Seven studies were completed as part of this regional study of the possible impact of climatic warming on California (Figure 4-3). These studies were quantitatively integrated as much as possible within the overall timeframe of this Report to Congress to obtain as complete a picture of those impacts as possible.

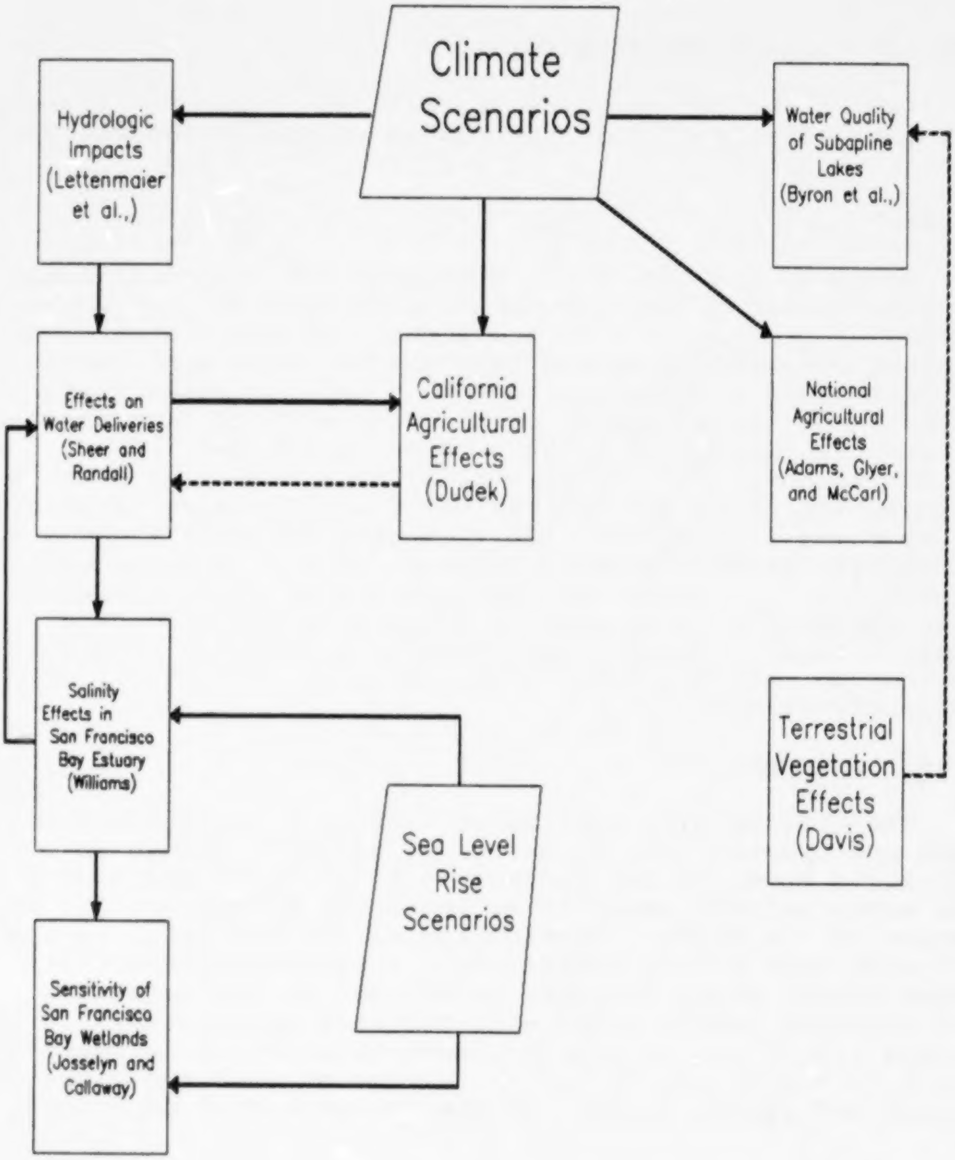
Climate Scenarios
Hydrologic Impacts (Lettenmaier et al.,)
Water Quality of Subapline Lakes (Byron et al.,)
Effects on Water Deliveries (Sheer and Randall)
California Agricultural Effects (Dudek)
National Agricultural Effects (Adams, Glyer, and McCarl)
Salinity Effects in San Francisco Bay Estuary (Williams)
Terrestrial Vegetation Effects (Davis)
Sea Level Rise Scenarios
Sensitivity of San Francisco Bay Wetlands (Josselyn and Callaway)

Figure 4-3. Organization of the study, showing paths of data input from scenarios and between projects (solid lines). Dashed lines indicate some important information flows that were not directly addressed in this study.

Also, several of the national studies have results pertaining to California.

Water is a key limiting resource in both managed and unmanaged ecosystems in the Central Valley Basin, and freshwater is important in estuarine ecosystems in the delta region. Consequently, the California studies were organized so that the impacts of climatic warming on the entire hydrologic system could be examined, starting at subalpine lakes in the mountains surrounding the valley and finishing at the freshwater outflow into the delta region and estuary (Figure 4-3). The individual projects examined the potential impacts of climatic change and sea level rise on particular ecosystems and water-delivery systems in the Central Valley. (See Methodology chapter of this report.) One of the major goals of this regional study was to determine the amount of runoff that would flow into the Central Valley from the surrounding mountains under different scenarios of climatic change, how much of that runoff would be available for delivery to the water users in the State, and how much would reach the delta.

Analyses Performed for this Study

- Hydrologic Effects on Central Valley Basin Rivers - Lettenmaier and Gan, University of Washington, and Dawdy, consultant.

The Lettenmaier et al. project (volume x) is the first of a series of four projects that are designed to determine the impact of climatic change on runoff and water deliveries within the Central Valley basin (Figures 4-3 and 4-4). Their project was designed to estimate changes in runoff from the mountains to the water resource system in the floor of the valley. Lettenmaier et al. used data from climate scenarios supplied to them by EPA as input to their modeling studies (see Scenario chapter and later section in this chapter on the California scenarios).

- Effects on Water Deliveries - Sheer and Randall, Water Resources Management, Inc.

Sheer and Randall (volume x) used the projected runoff from the mountains determined by Lettenmaier et al. to simulate the

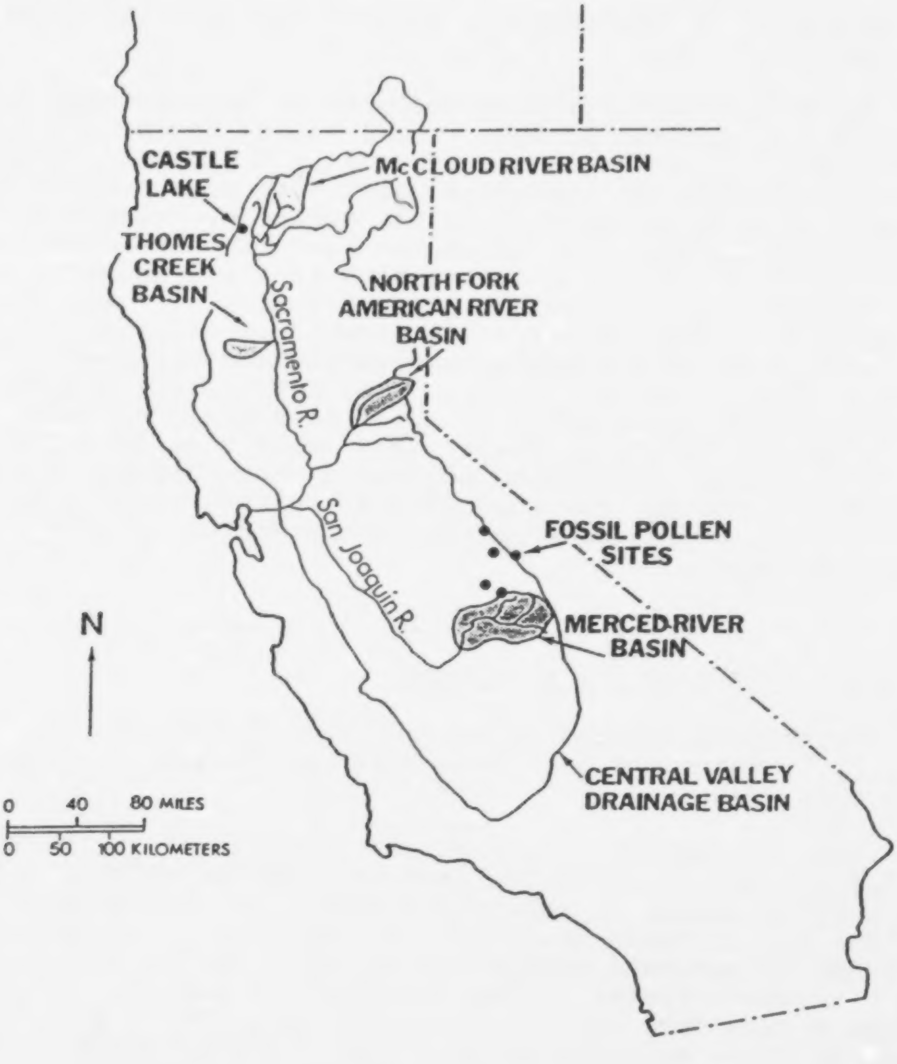
CASTLE LAKE
McCLOUD RIVER BASIN
THOMES CREEK BASIN
Sacramento R.
NORTH FORK AMERICAN RIVER BASIN
San Joaquin R.
FOSSIL POLLEN SITES
MERCED RIVER BASIN
N
0 40 80 MILES
0 50 100 KILOMETERS
CENTRAL VALLEY DRAINAGE BASIN

Figure 4-4. The Central Valley Drainage Basin of California. Shaded areas refer to the four study catchments used by Lettenmaier et al. The positions of the Castle Lake study site (Byron et al.) and the five fossil pollen sites (Davis) are indicated by dots.

response of the water supply and delivery systems of the Central Valley and State Water Projects to climatic change. Output from this project includes projected total water deliveries to the water users in the state.

- Salinity Effects in San Francisco Bay Estuary - Williams, Philip Williams and Associates.

Determining the impact of sea level rise and changing freshwater outflow into the Delta on salinity within the bay was the main goal of Williams' project (volume x). Williams also determined how much carriage water might be required to hold back salinity intrusions from the Delta pumping plants after sea level rise. The new carriage water requirements were than factored into Sheer and Randall's simulation of the water resource system, and represents an important feedback between the hydrologic effects of climatic change and sea level rise effects in the Delta (Figure 4-3).

- Effects on Wetlands in San Francisco Bay Estuary - Josselyn and Callaway, San Francisco State University.

Josselyn and Callaway (volume x) used results from Williams and Park (Sea Level Rise chapter) to assess the impact of changing salinity (as determined in Williams' project) and sea level rise on the wetlands within San Francisco Bay.

- Effects on California Agriculture - Dudek, Environmental Defense Fund.

Dudek (volume x) simulated the impact of changing climate on California agriculture. Besides using the climate data from the different climate scenarios, Dudek used estimates of mean annual water deliveries for irrigation under the different climate scenarios as input to his model of agricultural effects. One of the outputs of Dudek's study is an estimate of how water usage by agriculture could change under the different climate scenarios. This information was qualitatively used to compare available future water supplies and future water demand (Figure 4-3).

- Water Quality of Subalpine Lakes - Byron, Jassby, and Goldman, University of California at Davis.

Byron et al. (volume x) studied the impact of climate change on the water quality of a subalpine lake in northern California (Figure 4-4).

National Studies That Included California Results

- Economic Effects on Agriculture - Adams and Glyer, Oregon State University, and McCarl, Texas A&M University.

Adams et al. (volume x) conducted a national study of agriculture to estimate shifts in land and water use, and results pertaining to California are discussed in this chapter.

- Response of Vegetation to Past Climatic Changes - Davis, University of Arizona.

Davis (volume x) reconstructed the vegetation present in the Sierra Nevada during warm analogue periods of the Holocene to estimate the potential impact of warming on the present day vegetation in these mountains (Figure 4-4).

- Electrical Demand - Linder and Inglis, ICF, Inc.

As part of a national study, Linder and Inglis (volume x) estimated future northern Californian electrical demands in response to climatic change.

Air Pollution - Morris et al., Systems Applications, Inc.

Morris et al. (volume x) describe possible interactions of climatic change and air pollution. Results pertaining to California are discussed in this chapter.

CALIFORNIA REGIONAL CLIMATE SCENARIOS

Results from two GCM gridpoints were used to drive the effects models used in the California studies. (See the Methods chapter of this report for a discussion of how scenarios were developed and applied.) Both gridpoints lie at 120°W, with the northern gridpoint near the Oregon-California border and the southern gridpoint south of Sacramento (Figure 4-1). Average temperature and precipitation changes for both gridpoints are displayed in Figure 4-5. Generally large seasonal increase in mean temperature are projected by the models. Winter temperatures are between 1.9°C (OSU) and 4.9°C (GISS) warmer, and summer temperatures are between 3.1°C (OSU) and 4.5°C (GISS and GFDL) warmer. The OSU model generally projects less warming than the other two GCM models.

Annual precipitation increases in GISS by 0.28 mm/day, remains virtually unchanges in GFDL, and falls in OSU by 0.1 mm/day. Seasonal changes are more varied with spring rainfall in GFDL, 0.17 mm/day lower, with summer and fall rainfall in OSU being 0.32 to 0.35 mm/day lower. Rainfall in GISS increases in all seasons.

Overall, the OSU scenario represents less of a change from the present climate, and GFDL and GISS show larger temperature changes. The GISS scenario has higher precipitation than the other two scenarios. Generally, temperature increases are larger in the northern gridpoints than in the southern gridpoints. Annual precipitation is higher in the north in GISS and shows little regional difference for the other models.

RESULTS OF THE CALIFORNIA STUDIES

Hydrology of Catchments in the Central Valley Basin

Changes in mountain snowpack and runoff could have a major impact on water supply and quality in the Central Valley Basin. A hydrologic modeling approach was used by Lettenmaier et al. to simulate runoff under different climate scenarios, and these estimates then served as input to the simulation of the response of the water resource systems in the Central Valley Basin to climatic change (Sheer and Randall, Volume x).

Study Design

The approach taken was to model the hydrologic response of four representative medium-sized catchments in the Central Valley Basin and based on these four catchments, estimate streamflows for 13 larger subbasins in the Central Valley Basin. The four catchments chosen (Figure 4-4) for modeling range in size from 526 to 927 km^2 (203 to 358 mi^2). Outflows for each basin were determined using two hydrologic models that estimate snow accumulation, ablation, and daily runoff. The models were calibrated using a subset of the historic record and were verified using an independent subset of the data.

Lettenmaier et al. developed two additional climate scenarios to test the sensitivity of the results to changes in

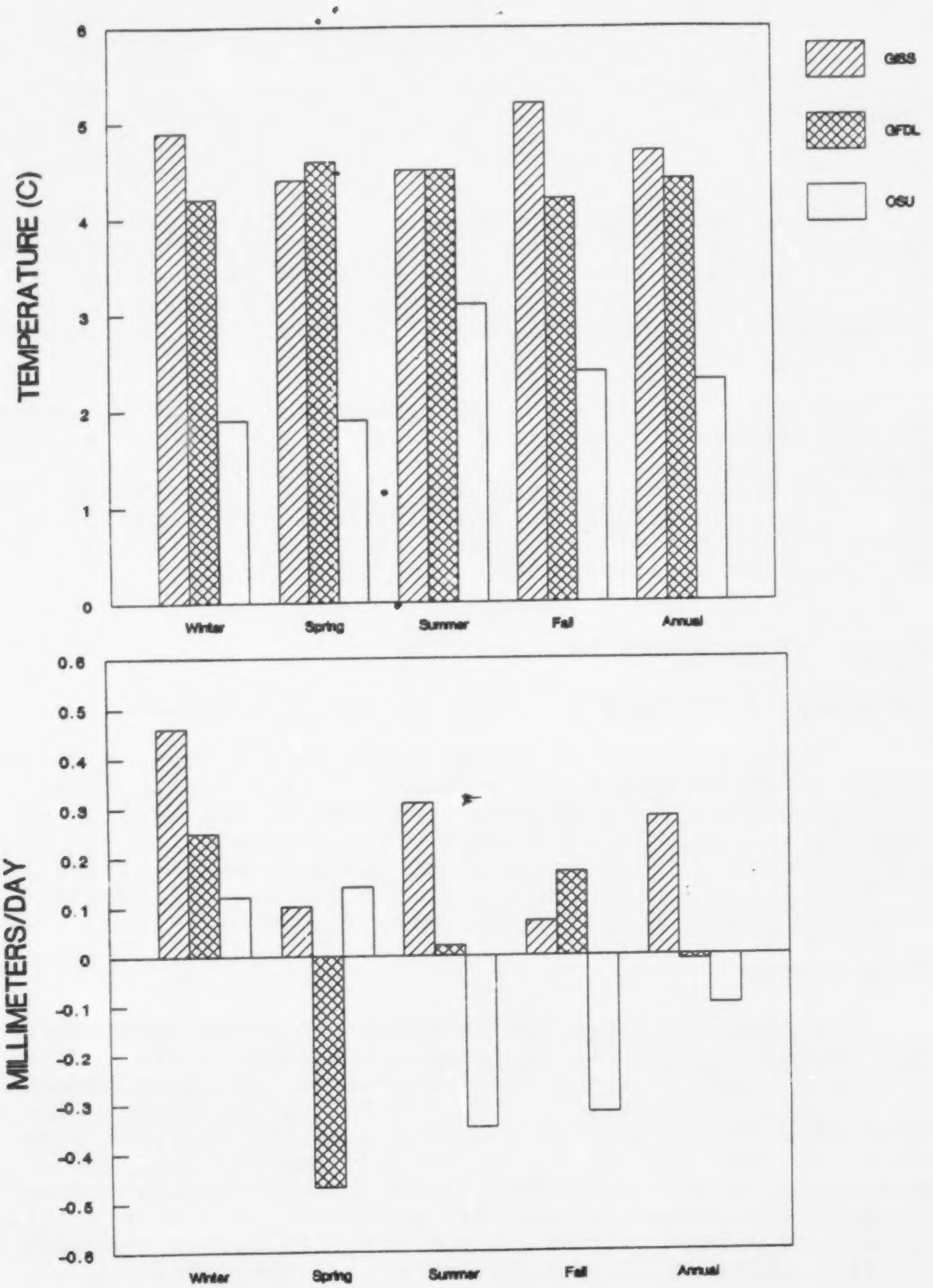

Figure 4-5. General Circulation Model (GCM) scenario results showing seasonal and annual (a) temperature changes and annual (b) precipitation ratios between GCM model runs at double current carbon between GCM model runs at double current carbon dioxide concentrations ($2xCO_2$) and at current dioxide concentrations ($1xCO_2$).

the scenarios. First, to determine the sensitivity to temperature alone, they developed a scenario with only the GISS $2xCO_2$ temperature estimates used and precipitation unchanged from the current values. Historic meteorologic data from the dry decade from 1931 to 1940 served as another scenario.

To provide input for the water resource simulation model of Sheer and Randall (Volume x), Lettenmaier et al. developed a statistical model that relates the historic flows in the four study catchments to historic flows from the 13 larger subbasins in the Central Valley basin. This statistical model was then used to estimate the flows in the 13 subbasins under the different climate scenarios.

Limitations

Results would be different if geographic and temporal variability were not held constant within each grid. Several assumptions made in this study are important considerations in terms of limitations of the results. The intensity of rainfall is the same. Fewer rainfall events of higher intensity could increase runoff relatively more than a greater number of rainfall events of lower intensity. One implicit assumption is that no long-term changes in vegetation cover and composition would occur, when in fact such changes are virtually certain (but their hydrologic manifestations are difficult to predict). If vegetation cover decreases, runoff could increase since less precipitation will be absorbed. Further, decreased cover may result in reductions in actual evapotranspiration and increased runoff.

Lettenmaier et al. assumed that the flows into the water resource system are adequately estimated from the study catchment flows using their statistical model. One limitation of this model is that the study catchments are at high elevations and their runoff is strongly affected by changes in snowfall, whereas some of the areas contributing runoff to the water resource system are at lower elevations with runoff driven primarily by rainfall under present climatic conditions. Since the principal change in the scenarios is a change in snowfall accumulation patterns, the statistical model is biased toward these effects and may somewhat overestimate the total effect of snowfall change on the water resource system. However, because basins at lower elevations have a relatively small impact on total hydrology, there is little bias in this approach.

Nevertheless, the results from this study are qualitatively robust, and any improvement in the hydrologic modeling probably would not alter the general nature of the results, although their precision probably would increase.

Results

Total annual runoff from the four subbasins remains about the same or increases slightly under the double CO_2 scenarios, but major changes occur in the seasonality of the runoff. Runoff could be higher in the winter months than it is today, because less of the precipitation would fall as snow and the snowpack could melt earlier (Figure 4-6a). As a consequence of higher early winter snowmelt, spring and summer runoff substantially decreases under these scenarios. The variability of the runoff could substantially increase in the winter months. Winter soil moisture could increase; evapotranspiration could increase in the spring; and late spring, summer, and fall soil moisture could decrease.

When only temperature changes are incorporated into the climate scenario and precipitation is held equal to the base case, total annual runoff is lower in all four catchments than in the scenario in which both temperature and precipitation were changed (Figure 4-6). However, the seasonal shift in runoff, which is the dominant effect of a general warming, is similar.

The scenario producing the most different results compared to the other scenarios is the 1930's analogue. In this case, runoff is lower in most months in the four subbasins, but the seasonal distribution of runoff is similar to the base case (Figure 4-6b). The reason for this difference is that the 1930's drought was mainly caused by a reduction in precipitation, rather than an increase in temperature, which is similar to the base case.

These results are consistent with those of Gleick (1987b), in that higher temperatures cause a major change in the seasonality of runoff. Since two different modeling approaches using many climate change scenarios produced similar results, these results can be viewed as relatively robust.

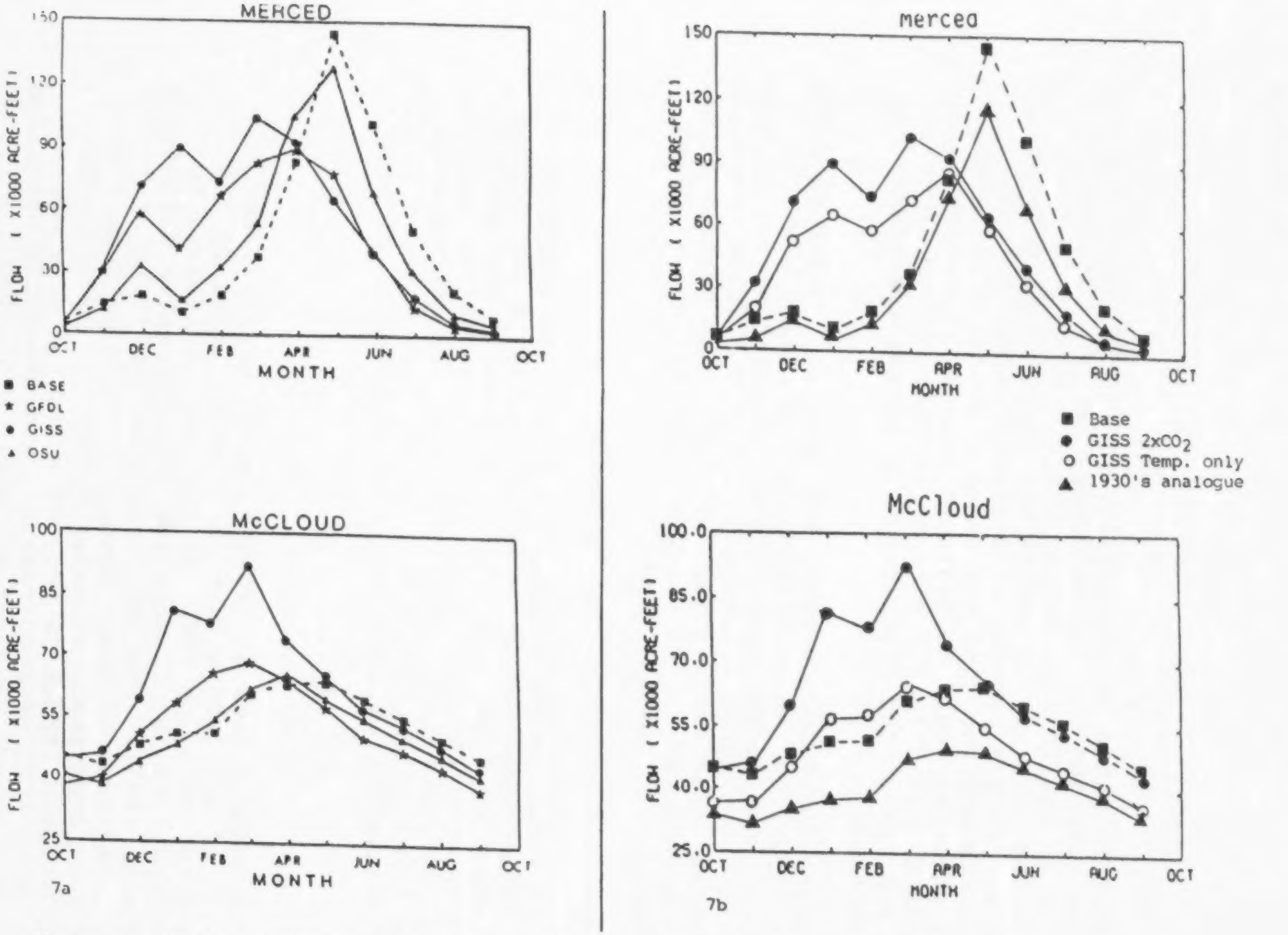

Figure 4-6. Mean monthly streamflows under different climate scenarios in two study catchments (see Figure 5 for locations of the study catchments). a. Results from the three GCM scenarios. b. Results from the scenario incorporating only the temperature change projected in the GISS model run, and from the 1930's analogue scenario.

Source: Lettermann et al, Volume __.

Implications

The potential change in seasonality of runoff could have significant implications for stream ecosystems and the water resource system in the Central Valley Basin. Reduction in streamflows in the late spring and summer could negatively affect aquatic organisms simply because of decreased water volume. Wildlife using streams for food and water also could be harmed. Water quality probably would be degraded because pollutants could become more concentrated in the streams as their flows decrease. The possible impacts on the water resource system are discussed in the next section.

The decrease in spring, summer, and fall soil moisture could have a strong impact on the vegetation in the basin, with plants adapted to drier conditions becoming more abundant at the expense of plants adapted to higher moisture conditions. These potential vegetation changes also could affect wildlife, and perhaps water quality, through changes in the nutrient composition of upland runoff and changes in erosion rates.

Water Resources in the Central Valley Basin

Changes in runoff under the different climate scenarios could have a major impact on the water resources in the Central Valley. The study by Sheer and Randall (Volume x) was designed to use estimates from Lettenmaier et al. of streamflows into the Central Valley to simulate how the water resource system would perform under these conditions. Particular importance is given to how water deliveries to users would be affected by climate change.

Study Design

Sheer and Randall used an existing model of the water resource system of California that is currently used by the Metropolitan Water District (MWD) of southern California to estimate the impact of the climate scenarios on water deliveries (Sheer and Baeck, 1987). The model emulates the State of California's Department of Water Resources Planning Simulation Model (California Department of Water Resources, 1986). The model used hydrologic inputs to project water use demands, instream and delta outflow requirements, and reservoir operating policies. Water demands were set at levels projected for 1990.

Two different sets of runs were made with the model. The first involved running the model for the different climate scenarios using current carriage water requirements. Williams (see Salinity in San Francisco Bay section of this chapter) determined that in response to rising sea level and levee failure, carriage water might have to be doubled to maintain the water quality at the delta pumping plants (see Figure 4-2). Consequently, Sheer and Randall ran the model a second time to determine the effects of doubling the carriage water requirement on water deliveries. Both simulations were run with a monthly time step, with water deliveries summarized on a yearly basis. Interannual variation is used as an indicator of reliability of delivery.

Sheer held a meeting with representatives of the State Department of Water Resources and the Bureau of Reclamation to discuss the results of his analyses and to get their response on how the water resource system would handle the changes in runoff.

Limitations

The limitations to Lettenmaier's study carry over to this one. Thus, interpretation of the results of the simulation of the water resource system's response to climatic change should focus on how the system deals with the change in seasonality of runoff, rather than the absolute values of the model output. Also, the model was run using 1990 conditions, and changes in future management practices, operating rules, physical facilities, water marketing, agriculture, and demand are not considered in the simulation.

Results

The simulation results suggest that both the amount and reliability of water deliveries could decrease after global warming. The decreases in mean annual SWP deliveries range from 7% (OSU) to 14% (GFDL) to 16% (GISS). In some years, the decreases are over 20% for all three double CO_2 scenarios. The projected decrease in water deliveries occurs despite a slight increase in precipitation over current levels in the climate scenarios and greater total outflow from the delta. Average monthly outflow from the delta increases in the late fall and winter under the climate scenarios and is lower in the spring (Figure 4-7).

The driving factor behind this decrease is the change in seasonality of runoff. Higher winter temperatures would lead to more of the winter precipitation in the mountains falling as rain rather than snow, and also to an earlier melt of the snowpack. Consequently more water would flow into the system early in the rainy season. Given current operating rules, the current reservoirs would not have the capacity to store the early runoff and at the same time retain flood control capabilities. Thus, in the simulation, much of the early runoff must be released, resulting in less water in storage at the end of the rainy season and lower water deliveries during the dry summer months. With system changes, it would be possible to store the extra runoff. The shift in the seasonality of runoff and the response of the water resource system to that shift drives the changes in monthly delta outflow (Figure 4-7).

Doubling the carriage water requirement in the model run for the GISS scenario only minimally affects SWP deliveries. This is because the baseline period (1951-80) does not include a lengthy drought period, during which the doubled carriage water requirement could have a substantial impact on deliveries.

The consensus of the meeting of the representatives from the State DWR and the Bureau of Reclamation concerning the potential changes in the seasonality of runoff is that the magnitude of this change is such that operational changes alone would not markedly improve the system's performance. One factor limiting the potential for adjusting the system to the projected changes is the likely need to provide for additional flood control storage during the winter months because of higher peak flows.

Implications

Under the three double CO_2 climate scenarios, water deliveries are less than the base case and could fall short of 1990 demand. Moreover, if carriage water requirements are doubled, shortages during a prolonged drought could become more significant. In addition, users and managers project a water demand of 3.6 million acre feet (maf) by 2010 (California Department of Water Resources, 1983). This demand could not be reliably supplied under the current climate and resource system, and the shortage might be exacerbated under the three double CO_2 scenarios. The potential decrease in water deliveries could affect urban, agricultural, and industrial water users in the state. How the potential decrease should be managed has many policy implications, which are discussed at the end of this chapter.

On the other hand, the increase in delta outflow shows that more water could flow through the Central Valley Basin under these scenarios, and water deliveries could be increased if major new storage facilities were constructed. However, this would be an environmentally and politically controversial option (see Policy section).

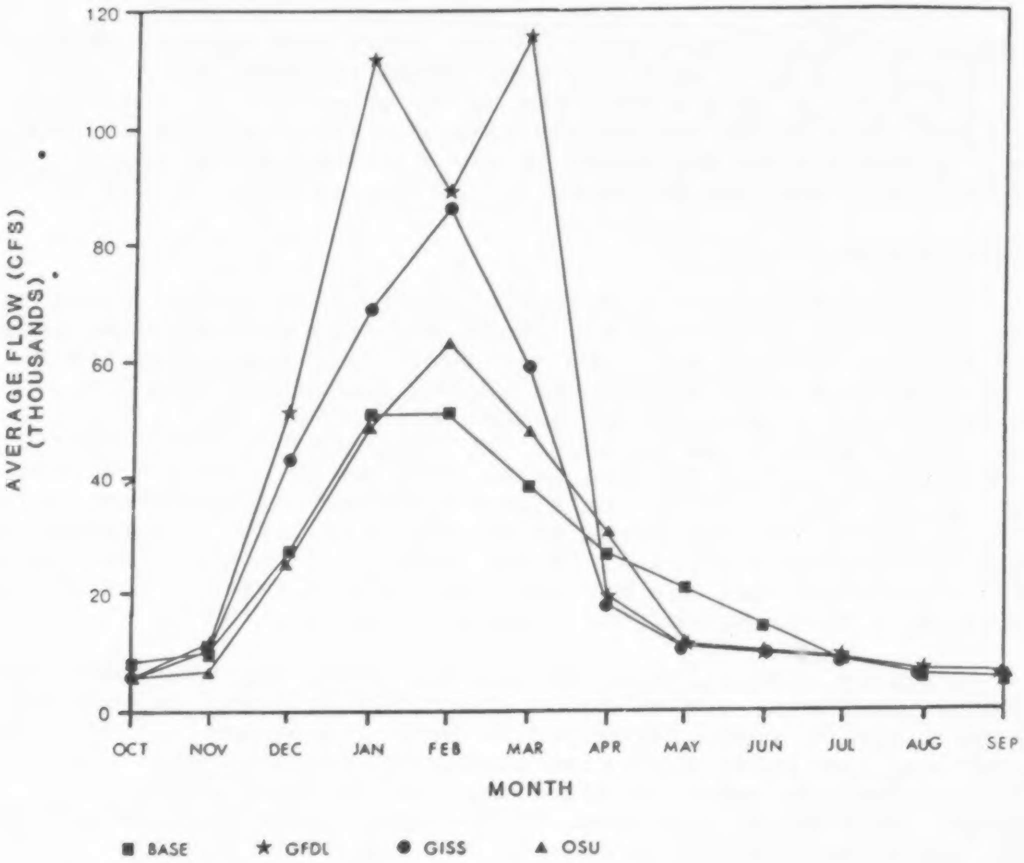

Figure 4-7. Projected monthly Delta Outflows under Different General Circulation Model Climate Scenarios.

Source: Adapted from Sheer, Volume __.

Salinity in San Francisco Bay

Climate change could affect the San Francisco Bay estuary in two ways: first, changes in precipitation and temperatures could affect the amount of freshwater runoff that will flow into the bay; and second, global warming could cause sea level to rise because of thermal expansion of the water and glacial melting, which could in turn affect a wide range of physical characteristics in the bay. The major objective of the study by Williams (Volume x) was to estimate the implications of global warming and rising sea level on the size and shape (morphometry) of the San Francisco Bay estuary and on salinity in the estuary.

Study Design

Williams' project was conducted in three parts, using two sea level rise scenarios and delta outflows estimated by Sheer and Randall (Volume x). The sea level rise scenarios are a 1-m (40-inch) rise with the levees in the Sacramento San Joaquin Delta and San Francisco Bay proper maintained, and a 1-m sea level rise with levee failure. The first part of this study involved estimating how sea level rise would affect the shape of the bay by establishing the elevation/area and elevation/volume relationships for all areas below +3m (+10.0 ft) according to National Geodetic Vertical Datum (NGVD). Then the tidal exchange characteristics for the bay were determined for its future shape by using a tidal hydrodynamic model (Fischer, 1970).

Finally, the salinity in the bay under the combined impacts of sea level rise and changing delta outflows was calculated by using a mixing model developed by Denton and Hunt (1986). This model was run first with nine different constant delta outflows (all months the same) to establish new carriage water requirements after sea level rise. Once these were established, and Sheer and Randall (Volume x) had run their simulation model with the new requirements, the mixing model was run again to determine the salinity regime in the estuary after climatic change. Included in the model output are average monthly and average annual salinities in different parts of the estuary under the different scenarios.

Limitations

Because of the short time frame, Williams used some old and inaccurate surveys in the morphometric analysis instead of making new surveys. These could produce errors of plus or minus 20% in the estimates of the estuary's volume. In addition, some levees probably will be maintained under any delta management plan, and thus the flooding of the delta islands would not be as extensive as assumed in the levee failure scenario. Williams did not consider changes in siltation and erosion of sediments that would likely occur under the different climate change scenarios. However, erosion would probably have a significant impact on water flow in the delta. For instance, deepening of the tidal channels in the delta could lead to intrusion of salinity farther upstream than projected in this study. In addition, more sophisticated models of salinity and tidal ranges and exchanges might improve the accuracy of the results. Finally, the new carriage water requirements were based on a steady-state analysis (e.g., constant delta outflows). Changes in the hydraulics of the Sacramento, San Joaquin delta and Suisun Bay with sea level rise could increase these requirements. Williams' results should be viewed as a preliminary estimate of estuarine changes, with emphasis placed on the direction of change, rather than on the absolute amount of change.

Results

The morphometric analyses suggest that given a 1-m (40-inch) sea level rise and failure of the levees, the total area of the estuary might triple, and its volume could double. If the levees are maintained, the increases in area and volume could be about 30 and 15%, respectively (see Figure 4-2). Interestingly, the amount of sea level rise is less important to the physical size of the bay than whether or not the levees are maintained.

Under the sea level rise scenarios with levees maintained, tidal ranges do not change significantly from current conditions. If levees fail, downstream constrictions at Carquinez Strait and to the east of Suisun Bay (see Figure 4-2) limit tidal transport and reduce tidal range in the delta, assuming that erosion does not alter the tidal characteristics of the delta.

The results from the initial application of the salinity model to constant delta outflows indicate that monthly carriage water requirements might have to be doubled to repel saline water from the upper part of the delta. Also, whether or not the levees are maintained has little effect on the salinity regimes in the bay according to the model's results. However, because possible scouring of tidal channels is not incorporated into the model, the predicted salinity after levee failure is probably underestimated.

Using Sheer and Randall's estimated delta outflow with double carriage water, Williams also estimated annual salinity in the bay. The results suggest that after a climatic warming, a 1-

m sea level rise, and failure of the levees, water of a given average annual salinity could migrate inland between 4 km (2.5 miles) (GFDL scenario) and 9.6 km (6 miles) (OSU scenario) (Figure 4-8).

Williams also calculated the average monthly salinity for Suisun Bay for the three climate scenarios, levee failure, and double carriage water requirements. Monthly salinities are higher for all months compared to the base case, except for winter and early spring months in the GFDL scenario. The greatly increased runoff of the GFDL scenario (Figure 4-7) during these months kept the salinity at the same level as the base case. Williams also modeled how the frequency of a given salinity value in any month would change. For example, in June salinities that were exceeded in 50% of the years in the base case might be exceeded in 80% of the years in both the GFDL and OSU scenarios, because of the lower outflows predicted under these scenarios.

Implications

Rising sea level could place the delta islands under increased risk of inundation, not only because of higher water levels but also because the larger area and volume of the San Francisco Bay estuary could result in greater wave energy and higher erosion rates of the levees. Improving the levees just to protect them against flooding at the current sea level could cost at least $4 billion (California Department of Water Resources, 1982). With higher sea levels, the cost of maintaining the levees could increase.

The large water body created if all the levees fail will have a longer water residence time. This means that any contamination (salt or other pollutant) will be more difficult to flush out of the delta region. Also, if saline water fills the islands when levees fail, significant amounts of freshwater will be needed to flush out the salt.

Increasing salinity could necessitate increases in carriage water to maintain freshwater at the export point in the delta or could require developing a different method to convey freshwater from reservoirs to users. The increase in carriage water coupled with the decrease in reservoir storage would most likely mean reduction in water deliveries to at least some of the system's users during extended droughts. With higher future water demands, shortages caused by the higher carriage water requirements may not be limited to extended droughts.

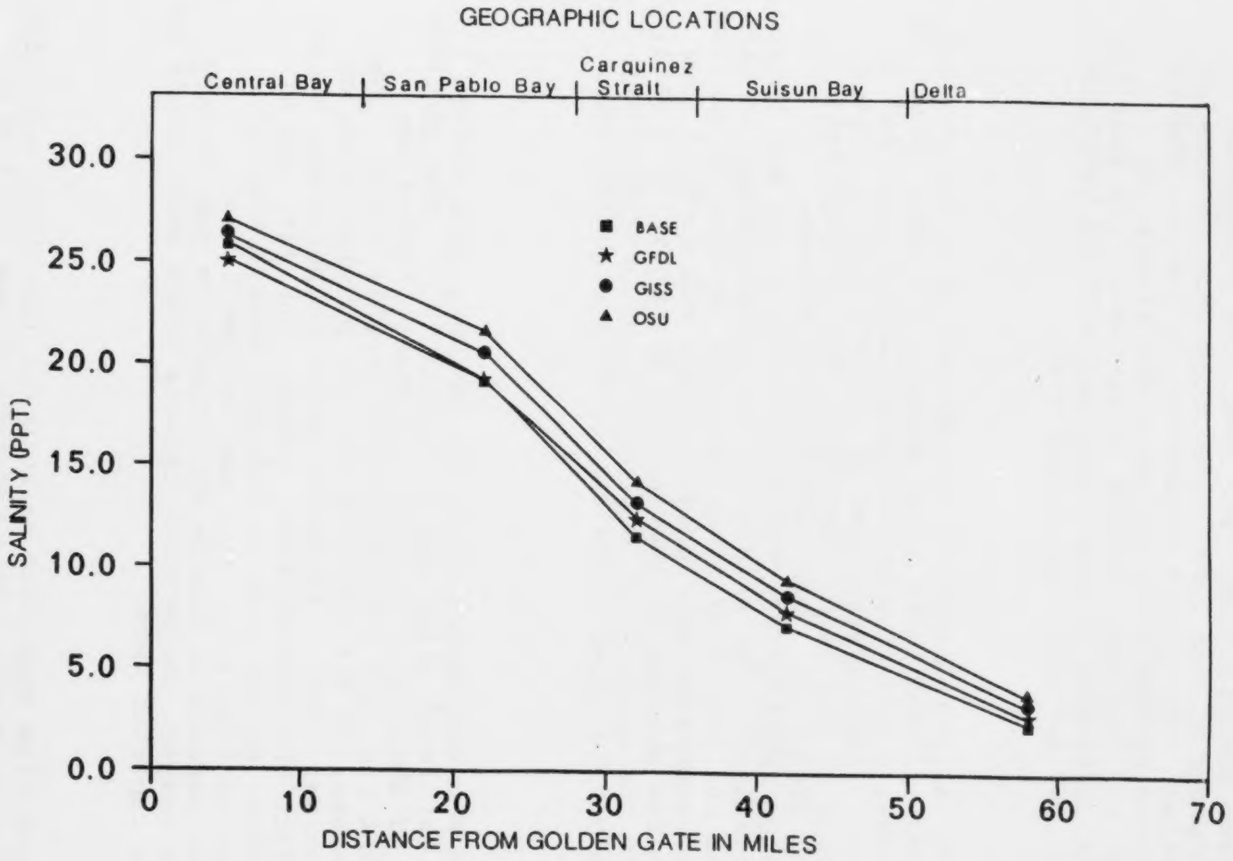

Figure 4-8. Average annual salinity in San Francisco Bay estuary under different hydrology scenarios versus distance from the Golden Gate. The corresponding geographic location of a particular distance is given at the top of the graph.

Source: Williams, Volume __.

Wetlands in the San Francisco Bay Estuary

Climatic warming could alter two important physical factors that affect wetland distribution: sea level and freshwater inflow. Major impacts of sea level rise could include erosion and marsh inundation. Changes in freshwater inflow can change the distribution and productivity of estuarine plants and animals. Josselyn and Callaway (Volume x) estimated the possible effects of climatic warming on deep-water and wetland habitats of the San Francisco Bay estuary (see Figure 4-2).

Study Design

Josselyn and Callaway examined the impacts of a 1-, 2-, and 3-m (40-, 80-, and 120-inch) sea level rise by the year 2100. Of the three scenarios, a 1-m rise by the year 2100 is regarded as the most realistic. Models were used to project nearly linear changes in the rate of sea level rise from 1990 through 2100 under these three scenarios. The relationship between sedimentation rates required for marsh maintenance and sea level rise rates was examined. The effects of salinity changes on the distributions and abundances of organisms were related to various freshwater inflow scenarios developed by Sheer and Randall (see Figure 4-7). In the absence of appropriate quantitative models, biotic changes in the estuary in response to changing salinity were qualitatively determined based on literature review and expert judgment.

Limitations

Circulation and sedimentation in the estuary will change dramatically as sea level rises and if levees fail. The specific characteristics of these biologically important changes are unknown at present and were not considered in this study. The sea level rise scenarios did not consider the possibilities of sudden changes in sea level. Increased water temperature, which may directly affect the reproduction, growth, and survival of estuarine organisms, or may have an indirect effect through changes in oxygen availability, also was not considered. Although specific impacts on plants and animals in the estuary are difficult to assess, the general impacts would most likely be similar to those reported here.

Results

Rates of sea level rise from 1990 to 2040 for the three scenarios are presented in Figure 4-9. Once the rate of sea level rise exceeds the rate of sediment accretion, tidal marsh habitats would become inundated and erosion of the marsh edge could increase. For the 1-m rise scenario, the rate of rise is not projected to exceed maximum accretion rates until about the year 2040, while the 2- and 3-m (80- and 120-inch) rise scenarios suggest rise rates in excess of accretion rates after 2010 and 2000, respectively.

Peak primary productivity, at present, occurs in early spring in San Pablo Bay and in the summer in Suisun Bay. These maximum productivity levels could be substantially reduced, particularly for brackish and freshwater plant species, under the higher salinities of the OSU scenario (see Figure 4-8), and peak spring production might shift upstream into the delta if levees fail. However, under GFDL and GISS conditions, the locations of maximum production levels might remain in their present positions if the levees are maintained. If the levees fail, primary production could increase in the extensive shallow water and mudflat areas created.

Since many areas currently protected by levees are 1 to 2 m (40 to 80 inches) or more below sea level, levee failure would cause them to become deepwater areas rather than marshes. Eventually, some of these formerly leveed areas might receive enough sediment deposition to support marsh development. Inundation of marshes and salinity impacts on freshwater and brackish-water plant species could reduce food and cover sources for waterfowl (see Figure 4-9). Loss of emergent vegetation could significantly reduce the numbers of migratory waterfowl using the managed wetlands along Suisun Bay's north shore.

If levees are maintained under conditions of sea level rise, salt may build up behind them from the evaporation of standing water. This salt will cause marsh vegetation to die back and will reduce the value of these wetlands to wildlife.

Freshwater inflows projected during springtime under the climatic change scenarios (see Figure 4-7) may be too low to support anadromous fish (saltwater fish that enter freshwater areas for spawning). Lower inflows could result in declines among these populations in this region (Kjeldson et al., 1981).

If levees fail, a large inland lake with fresh to brackish water quality could be created in the delta. Striped bass and shad spawn in essentially freshwater conditions and their spawning could be reduced under increased salinity, especially if they did not move upstream to relatively fresh water. Marine fish species could increase in abundance in the Suisun and San

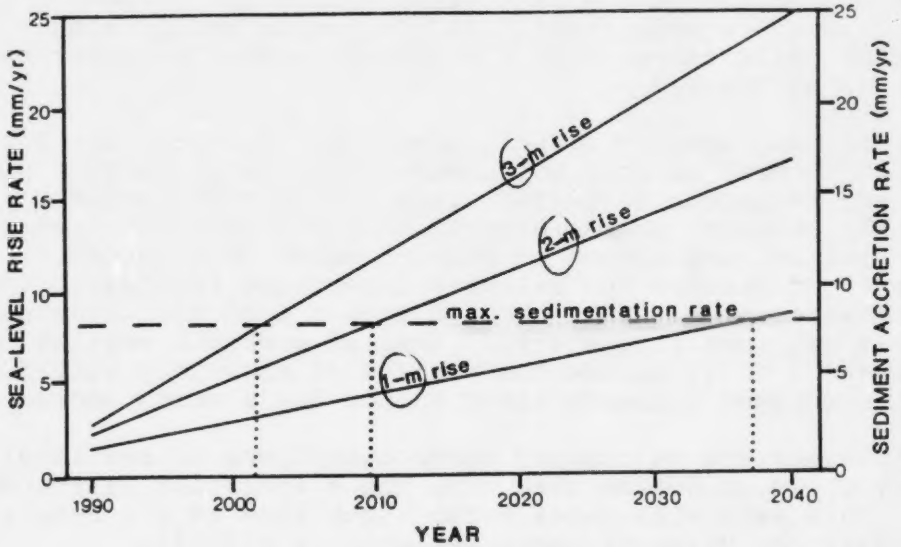

Figure 4-9. Sea level rates at San Francisco from 1990 to 2040 under 1-, 2-, and 3-m (40-, 80-, 120-inch) sea level rise scenarios. When the rate of sea level exceeds maximum recorded rates of sediment accretion, marsh habitats would most likely be converted to deeper-water habitats.

Source: Josselyn and Callaway, Volume __.

Pablo Bays in response to the higher salinities projected, and freshwater and anadromous species could decrease.

Implications

The loss of wetlands could result in substantial ecological and economic losses for the region. For example, the managed wetlands north of Suisun Bay support a hunting and fishing industry valued at over $150 million annually (Meyer, 1987). Tourism, hunting, fishing, rare and endangered species, and heritage values also could suffer.

California Agriculture

California's agricultural production is highly dependent on irrigation which accounts for approximately 80% of the states net annual water use. Dudek (volume x) used existing agro-ecological models to explore potential responses of California agriculture to climatic change.

Study Design

Climatic changes from the GISS and GFDL $2xCO_2$ scenarios were linked to an agricultural productivity model adapted from Doorenbos and Kassam (1979). Growth responses to both climatic change and climatic change plus CO_2 direct effects were modeled. These productivity responses were then introduced into the California Agriculture and Resources Model (CARM; Howitt and Mean, 1985) which estimates the economic and market implications of such changes. Mean surface water supplies under the base, GISS, and GFDL scenarios were calculated from the simulations of Sheer and Randall (volume x) and were input to CARM.

Limitations

Further, the CO_2 direct effects results should be viewed as preliminary since they are based on data from growth chamber experiments that may poorly represent field conditions. This study did not consider changes in agricultural technology, crop varieties, planting dates, or changes in water costs. Also, new crop/location combinations were not considered. The interaction between climatic change and CO_2 direct effects on productivity were not examined but may significantly limit potential growth increases. No national or international context of agricultural price signals were considered. These could be a major factor in determining how California farmers respond to climatic change. Given these limitations, realistic estimates of agricultural responses to climatic change may be difficult to obtain. The results may be more valuable as indications of potential trends rather than specific impacts.

Results

Relative to the 1985 base, average yields could be significantly reduced for California crops in response to climatic changes alone (i.e., without consideration of direct effects of CO_2). Generally, the greatest impacts are projected under the hotter GISS scenario. Table 1 presents regional yield changes for sugarbeets, corn, cotton, and tomatoes. These projections were generated by the agricultural productivity model and do not consider economic adustments or water supply limitations. Tomatoes might suffer the least damage, with average yields reduced from 5% to 15%. Sugarbeets could be hardest hit, with average declines from 20% to 40%. Yield reductions in sugarbeets are projected to be greatest in the relatively hot interior southern regions. Differences in growth response between the two climatic scenarios were greatest for corn and least for tomatoes.

Without economic adjustments, corn yields declined 20% to 41% as projected by the agricultural productivity model under the GISS scenario (Table 1). With economic adustments, declines of roughly 21% are projected (Table 1); a result at the lower end of the direct productivity impacts.

When the direct effects of CO_2 on crop yields are considered, yields of sugarbeets, cotton, and tomatoes generally increased over the 1985 base (Table 1). Corn is unable to increase growth in response to increases in CO_2 concentration, although yield reductions are not as great as with climate change along (Table 1). Cotton could benefit the most from inadvertant CO_2 fertilization with yield increases ranging from 6% to 41%.

Potential increases in yields in response to CO_2 fertilization might only be achieved at a cost of increased groundwater extraction in many areas. For example, when surface water utilization is projected at 100% of capacity, as in the Northern San Joaquin region, excess demand would require increased groundwater usage (Figure 4-10). However, increased crop yields may offset increased economic costs for water.

Regionally, across all scenarios, (not considering potential changes outside of California) the largest reductions in crop acreage are projected in the Imperial Valley while the delta

Table 1. Regional and statewide percentage yield changes (relative to 1985) under different General Circulation Model climate scenarios. Regional changes are projected by the Doorenbos and Kassam agricultural productivity model while statewide production changes are projected by the California Agriculture and Resources Model (CARM). The latter estimates include economic adjustment "Net" includes the direct effects of increases in CO_2 and climatic change (CC).

		Crop							
		sugarbeets		corn		cotton		tomatoes	
Region[b]	Scenario	CC	Net	CC	Net	CC	Net	CC	Net
South Coast									
Los Angeles	GISS	-26	21	-41	-37	-22	11	-7	18
	GFDL	-20	30	-26	-22	-4	41	-5	21
North Interior									
Red Bluff	GISS	-28	12	-27	-22	-18	22	-15	11
	GFDL	-23	21	-14	-8	-10	35	-13	13
Sacramento Valley									
Sacramento	GISS	-30	17	-20	-14	-17	25	-12	16
	GFDL	-27	22	-6	0	-11	34	-8	21
Southern San Joaquin									
Fresno	GISS	-33	5	-26	-21	-16	25	-15	11
	GFDL	-39	-8	-14	-8	-10	36	-13	14
Southern Deserts									
Blythe	GISS	-40	-2	-31	-27	-28	6	-13	13
	GFDL	-39	0	-14	-8	-19	21	-12	15
CARM Statewide									
	GISS	-30	12	-21	-17	-17	23	-13	5
	GFDL	-26	15	-9	-4	-10	35	-11	16

[1] refer to Figure 1 for city locations.
Source: Dudek, Volume __.

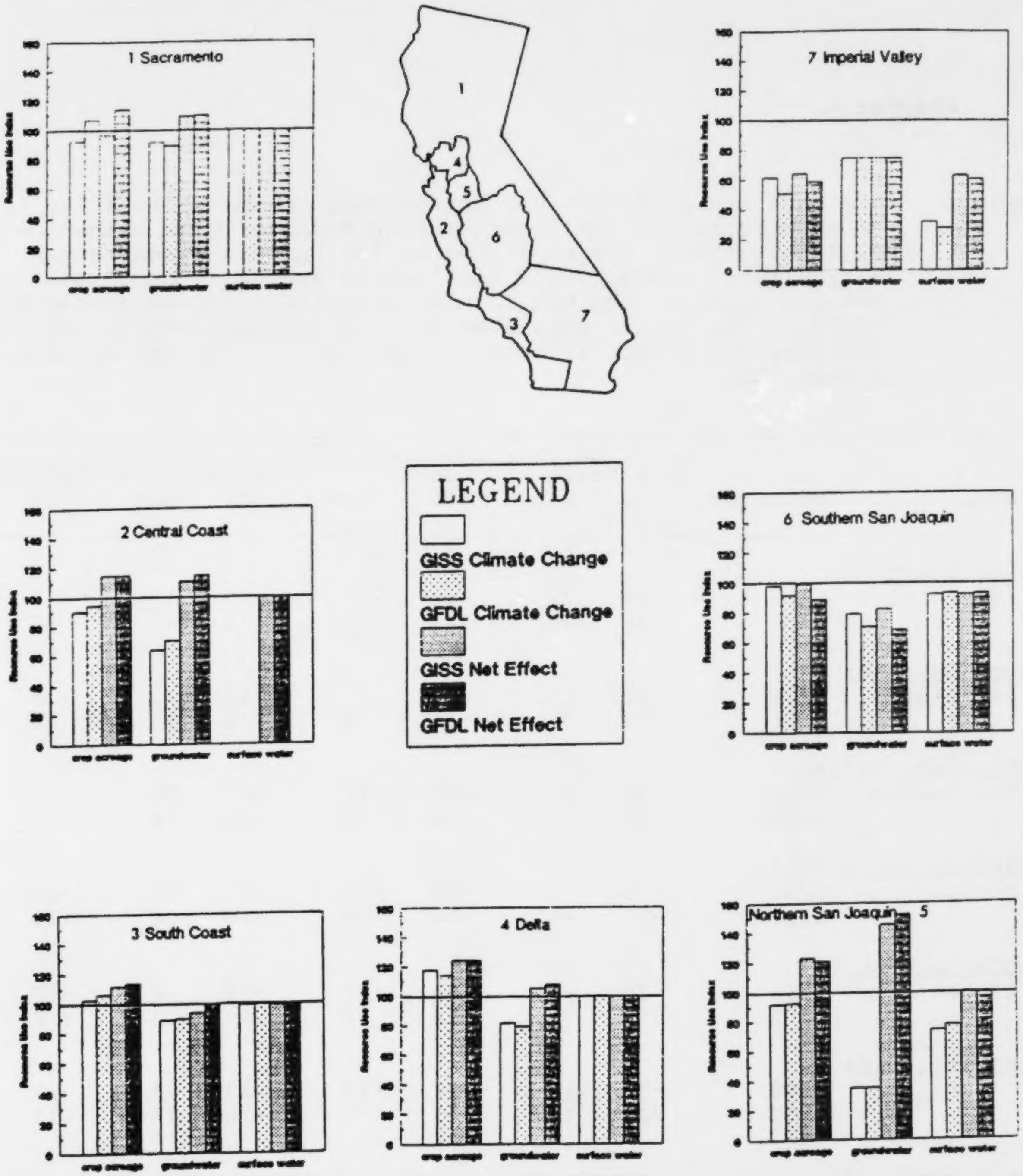

Figure 4-10. Regional crop acreage, groundwater use, and surface water use changes under different General Circulation Model climate scenarios. Net effect includes the direct effects of increases in CO_2 and climatic change.

Source: Dudek, Volume __.

region shows the largest gains in acreage (Figure 4-10). This expansion of agriculture in the delta region would depend on maintenance of levees protecting farmland. Without considering CO_2 fertilization, statewide crop acreage was reduced about 7% from the 1985 base. When CO_2 direct effects are considered, statewide crop acreage approximately equals 1985 base levels.

Implications

Regional changes in cropping locations and patterns of water use imply potential exacerbation of existing nonpoint source pollution and accelerated rates of groundwater overdraft with ensuing environmental impacts.

Changing water supply demands may result in increased conflicts between water users. In addition, shifts in the location of agricultural production could play a substantial role in the future viability of natural systems. Such shifts could also have a significant impact on the economic viability of small agricultural communities.

National Agriculture

Adams, et al. conducted a national agricultural study that includes results relevant to California (Adams et al., volume x). The results of the Adams et al. study are not directly comparable with the results from Dudeks' study (discussed above) since Adams et al. considered national agricultural impacts and aggregated California into a Pacific region with Oregon and Washington. Further, the two studies did not examine the same set of crops and modeled productivity differently (see the Agriculture chapter of this report for a description of the study's design and methodology).

Results

Nationally, Adams et al. (volume x) project 2% to 4% declines in crop acreage in response to climatic change but shows a 18% to 20% increase in acreage in the Pacific coast states. This increase in the Pacific region is attributable to the regions extensive use of irrigated agriculture. In contrast, most other regions of the U.S. predominantly use dryland farming and crop acreage might decline in response to moisture stress. The Adams et al. approach is based on maximizing farmers profits and indicates that higher yields associated with direct CO_2 effects might result in further declines in crop acreage (or, in the case of the Pacific coast states, less of an increase) since less acres might be required to produce the necessary crops.

Water Quality of Subalpine Lakes

Subalpine lakes are common in the California mountains, and many of these are the source of streams and rivers flowing down into the lowlands. Changes in the water quality of these lakes could significantly alter their species composition and nutrient dynamics and also could have an impact on downstream water quality and ecosystems. The sensitivity of California's subalpine lakes to weather variability and climate change has not been extensively studied. Consequently, Byron et al. studied how climate controls the water quality of Castle Lake, a subalpine lake in northern California.

Study Design

Goldman et al. (1989) correlated an index of water quality, primary production (i.e., the amount of biomass produced by algae in the lake), with climate variation at Castle Lake. Consequently, Byron et al. (Volume x) were able to develop empirical models relating primary production with various climate parameters.

Limitations

The model is limited to estimating annual values of primary production; seasonal variability is not calculated. The model also does not project changes in species composition and nutrient dynamics, which could have important consequences for water quality. Changes in upland vegetation and nutrient cycling, which could also affect the lake's water quality, were not part of the model.

The estimates of annual primary production produced by this model are relatively precise, although the results are general in the sense that no species-specific projections are made.

Results

The model projects that mean annual primary production could increase under all three of the double CO_2 scenarios, with increases ranging from 16% (OSU scenario) to 87% (GISS scenario) (Figure 4-11). The OSU results are within one standard error of present productivity, and thus do not represent a significant decrease in water quality. The transient scenario produced generally increasing but variable primary production estimates, with the mean production of the last decade in the transient scenario about 25% higher than the base (control) case.

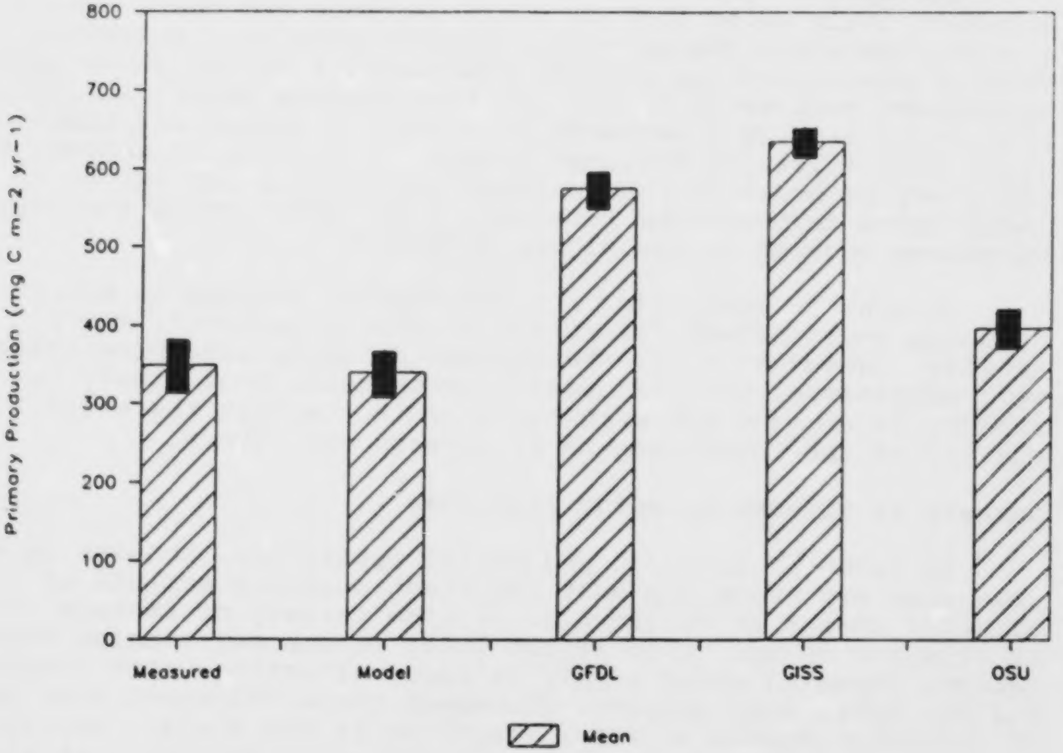

Figure 4-11. Annual primary production estimates for Castle Lake showing actual and model values for present conditions and model values for three General Circulation Model climate scenarios (see Figure 4 for location of Castle Lake). The solid bars show one standard error for each estimate.

The increase in annual primary production is attributed principally to the temperature increase projected by the scenarios. The higher temperatures resulted in less snow accumulation, which is correlated with an earlier melting of the lake ice, and a longer growing season.

Implications

Higher primary production could result in climatic effects being indirectly felt at higher points in the food web in the lake and could affect the lake's nutrient dynamics.

Extrapolating these results to other subalpine lakes suggests their water quality could decrease and their species composition might change after climatic warming. Increased primary production can provide additional food for other aquatic organisms, such as fish, but can also degrade water quality by ultimately causing a decrease in dissolved oxygen and blocking light from filtering to lower levels. Fisheries in unproductive lakes may be enhanced, while trout populations may suffer in lakes where temperatures rise past a threshold value and oxygen decreases because of the higher production.

Changes in production and concomitant changes in nutrient dynamics could affect downstream river and reservoir water quality. However, since the streams draining subalpine lakes are well oxygenated, the increased biomass would most likely be rapidly decomposed and probably would not affect the water quality of the lower reaches of streams and rivers.

Summary of Effects on Water Resources

In terms of economic and social importance, changes in water resources are among the most important possible effects of climatic change in California. A wide variety of factors related to climatic change could affect water resources, ranging from factors changing water supply to those affecting water demand. All the individual projects discussed above addressed some aspect of climatic impacts on water resources in the State. However, these studies did not consider all the major factors that will affect California water resources in the next century, mainly because of the complexity and inherent difficulties in forecasting future demand for water. This section discusses other factors that will affect future water demands that were not directly considered by the individual studies, including future changes in agriculture, population, water efficiencies, and sources of water, including groundwater.

Dudek's study used estimates of water deliveries from Sheer and Randall's study, but changes in agriculture that he determined, and hence changes in agricultural demand for water, are not factored back into the water simulation model. For instance, Dudek's results indicate that because of climatic conditions, crop acreage in the Imperial Valley decreases, freeing water used there for irrigation to be used elsewhere in the State. Also, as cropping patterns change, so would the pattern of needed water transfers via the water resource system, thus affecting water deliveries. Finally, Dudek found that groundwater usage could increase after climatic change when the direct effects of CO_2 are included in his model. Estimated groundwater usage increases when full use of surficial water sources does not meet agricultural demands estimated in the model. Thus, Dudek's results suggest that agricultural demand for water could exceed surficial supplies after climatic warming, further exacerbating water shortages.

Not considered in the overall California study, but critical to determining the magnitude of potential water shortages in the next century, are population growth and accompanying changes in water demands. Projections of population growth place the State's population at about 35 million in 2010 compared with 24 million in 1980, an increase of 45% (California Department of Water Resources, 1983). An increase of this magnitude will significantly intensify municipal water demands, exacerbating shortfalls. Meeting the needs of the growing population in face of competing demands from agriculture raises some important policy questions that are discussed in the policy section.

If water shortages become more common, it is reasonable to assume that agricultural, industrial, and residential users will change water-use efficiency. Changes in efficiency were not considered in any of these projects but could moderate possible future shortages. Any change in water pricing or water law also could affect water demand and supply, but these factors are probably impossible to project very far into the future.

Groundwater usage is discussed in Dudek, but the overall impacts of climatic change on groundwater are not addressed in this project. As demand for water increases beyond the capability of the water resource system to deliver the needed water, mining of groundwater (as Dudek shows for agriculture) is one option users could adopt to meet their demand. Using groundwater could lessen the severity of water shortages in the short term but presents environmental problems, such as land subsidence, over the long term.

In general, given the current water resource system, the projected response of that system to climatic change and qualitative considerations of future changes in water demand suggest that water shortages could be significantly greater than estimated here.

Vegetation of the Sierra Nevada

To better understand the sensitivity of natural vegetation in California, Davis studied how the terrestrial vegetation growing in the California Sierra Nevada has changed over the past 12,000 years. The climatic changes that occurred during this period suggest how the vegetation that currently exists in the mountains could respond to future climatic changes. In particular, the middle latitudes of the Northern Hemisphere are believed to have been warmest (1-3°C warmer than today) about 6,000 years ago (Budyko, 1982), and parts of western North America were apparently warmest 9,000 years ago (Ritchie et al., 1983; Davis et al., 1986). Thus, the period that existed between 6,000 and 9,000 years ago in California could present a possible analogue to a warmer future climate.

Study Design

The composition of the vegetation that has existed in the central Sierra Nevada over the last 12,000 years was determined using fossil pollen analysis. Fossil pollen samples were collected from five lakes situated along an east-west transect (see Figure 4-4) passing through the major vegetation zones of the Sierra Nevada. Dissimilarity values were calculated between modern and fossil pollen samples to determine the past vegetation at a particular site.

Limitations

The climate projected in the three double CO_2 scenarios is different from the climate that probably existed between 6,000 and 9,000 years ago in the Sierra Nevada, according to Davis. The vegetation that persisted then suggests that the climate was drier and a little cooler than it is today. This is a marked contrast to the warmer and slightly wetter climate scenarios used in this report. Consequently, the results from this study do not provide a past analogue for the climate scenarios, but nonetheless present a possible analogue for how Sierra Nevada vegetation could respond to a warmer Northern Hemisphere climate.

A relatively small set of modern pollen samples was available for comparison to the fossil samples; therefore, the precision of the vegetation reconstruction is somewhat uncertain. Also, the precision of the estimated elevational shifts in the vegetation zones is low because of the limited number of fossil sites available for the analysis. Nevertheless, this study provides a good general summary of the vegetation changes in the Sierra Nevada during the past 12,000 years.

Results

The forests existing in the western Sierra Nevada 9,000 years ago resembled those found east of the crest today (Figure 4-12), with lower forest cover and tree density. Pine and fir densities, in particular, were lower. Between 9,000 and 6,000 years ago, the vegetation gradually became similar to the modern vegetation in the same area, and by 6,000 years ago the modern vegetation zones were established on both sides of the Sierra crest. The vegetation at 6,000 years ago is subtly different from that in the area today, with less fir and more sage. The forests may have been slightly more open than today.

Implications

If climatic conditions of the Sierra Nevada in the next century are similar to those that existed 9,000 years ago, major changes could occur in the forests of the region, both in composition and density. The vegetation changes could generate significant environmental impacts, ranging from changes in evapotranspiration and related feedbacks to local hydrology, to changes in nutrient cycling and soils, which could degrade the water quality of mountain streams. Fire frequencies could increase as a function of changes in fuel loads, ignition frequencies, and vegetation. If dead wood rapidly builds up because of the decline in one or more tree species, large catastrophic fires could occur.

If future forests west of the Sierra crest become more similar to current forests east of the crest, timber production could significantly decline. Based on National Forest Inventory data, timberlands east of the crest currently support only about 60% of the wood volume of timberlands west of the crest (U.S. Forest Service, Portland, Oregon, personal communication). The different climate could also necessitate a change in timber practices (e.g., reforestation techniques).

Vegetation change in response to climatic change could produce additional stress for endangered animal species as their preferred habitats change. Populations of nonendangered wildlife also could be affected as vegetation changed, with some species

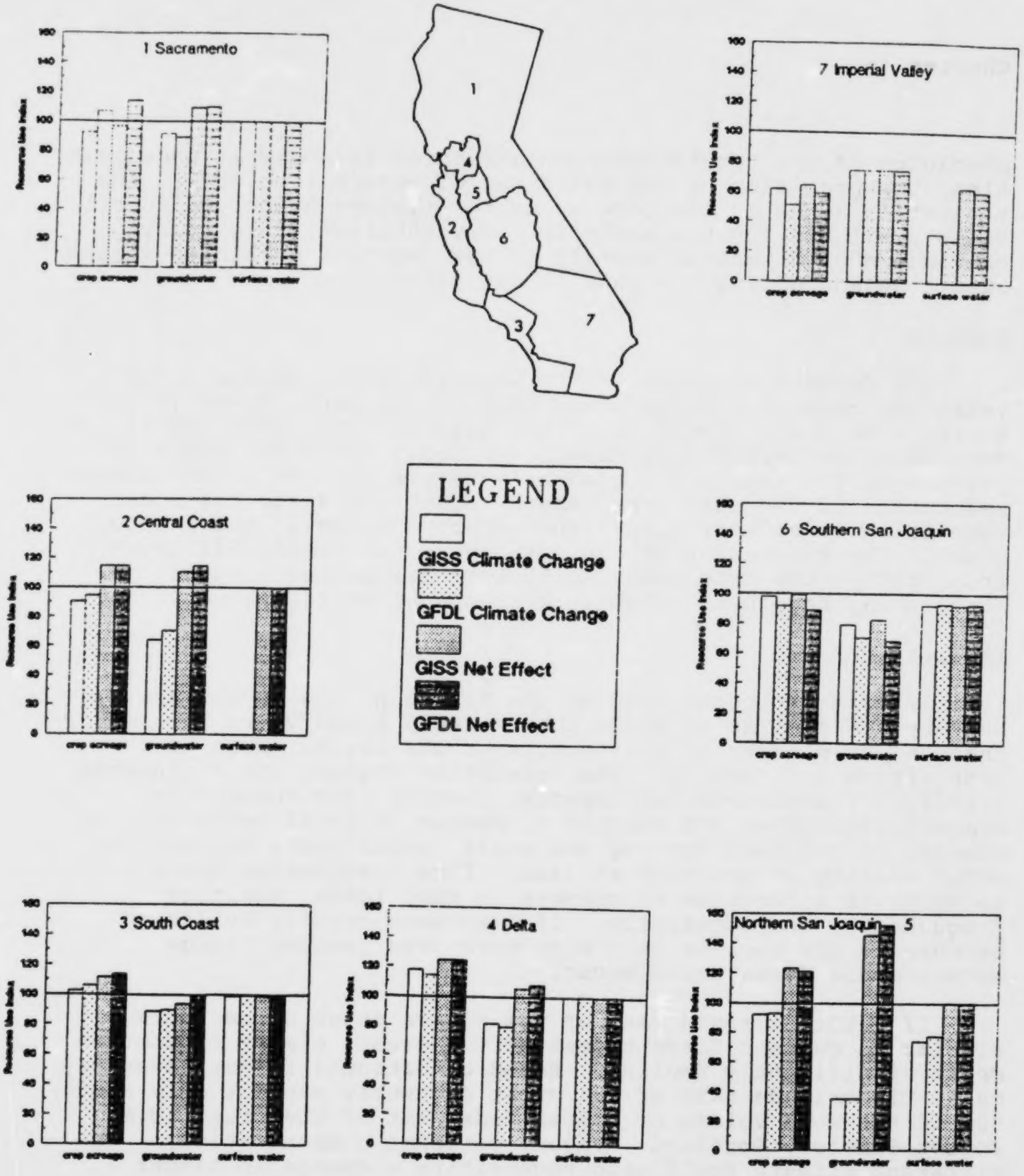

Figure 4-12. Regional crop acreage, groundwater use, and surface water use changes under different General Circulation Model climate scenarios. Net effect includes the direct effects of increases in CO_2 and climatic change.

increasing in abundance and others decreasing. Some plant species, especially alpine species, also could become endangered. Warmer temperatures could favor subalpine species over alpine species at some of the higher elevation peaks and ridges in the Sierra Nevada, leading to local extinction of the alpine species.

Electricity Demand

The electric power industry is highly sensitive to uncertainty in future energy demands associated with potential climate change. As part of a national study, Linder and Inglis estimated northern California's energy demand for the years 2010 and 2055. (See the Energy Demand chapter of this report for a description of the study's design and methodology.)

Results

In California, climatic change scenarios result in only small changes in electrical utility generation and costs by the year 2010. Annual power generation is estimated to increase by 1 to 2%, and new generation capacity requirements would be less than 1% greater than increases without climate change. By the year 2055, annual power generation is estimated to increase by 3 to 5%, and new generation capacity requirements would be 14 to 20% greater than non-climate induced needs. Then, cumulative investments in new capacity would cost $10 to $27 billion.

Implications

More powerplants may need to be built; these will need more cooling water, further depleting the water supply. Climate-induced changes in hydrology may reduce hydropower generation and increase dependence on fossil fuels and nuclear power. Increased use of fossil fuels may provide positive feedback for the greenhouse effect and may deteriorate local air quality.

Air Pollution

Morris et al. (Volume x) studied possible interactions of climatic change and air pollution in California. (The study's design and methodology are discussed in the Air Quality chapter of this report.)

Results

Morris et al. (Volume x) project an increase in ozone concentration of up to 20% during some days in August in response to a 4°C (7°F) climatic warming in central California. The

National Ambient Air Quality Standard (NAAQS) for ozone is 12 ppm. The modeling of Morris et al. estimates a 30% increase in August days that exceed this standard. Furthermore, the area exceeding the NAAQS could increase by 1,900 km^2 (730 mi^2), and the number of people exposed to these elevated ozone levels could increase by over 450,000.

Implications

The greenhouse effect climatic changes may significantly change the air's chemistry on urban and regional scales. These changes may exacerbate existing air quality problems around California metropolitan areas and agricultural areas of the Central Valley.

POLICY IMPLICATIONS

An overall question that applies to resource management in general is, "What is the most efficient way to manage natural resources?" Currently, management is based on governmental jurisdiction with, for example, forests managed at the local, State, or Federal level. Management of hydrologic systems is also based on governmental jurisdiction. An alternative would be to manage these systems using natural boundaries as the criteria for determining management jurisdiction. The pros and cons of such a management strategy deserve at least some preliminary research.

Water Supply and Flood Control

Water supply is the basis for most economic development in California. Yet, almost all the water available in the SWP is allocated for use. A major problem is to accommodate rising demand for water, interannual climate fluctuations, and the need to export water from northern California to southern California.

In addition, the results from these studies suggest that climate change over the next 100 years could cause earlier runoff, thus reducing water deliveries below their projected 1990 level. This situation would create a set of major policy problems for the water managers and land use planners in California.

Two major policy questions can be raised concerning the possible reduction in water deliveries: How can the water resource system be changed to prevent a decrease in water deliveries caused by climate change? If water deliveries fall short of demand, how should potential water shortages be allocated?

Approaches for Modifying the Water Resource System

Several possible approaches can be attempted to increase water deliveries. First, management of the system could be modified. For instance, the most recent SWP development plan suggests the possibility of State management of both SWP and CVP facilities (California Department of Water Resources, 1987a). Complete joint management could produce more than 1 million acre feet (maf) additional reliable yield in the system. Steps toward greater cooperation have been taken. The Coordinated Operating Agreement (H.R. 3113) between the SWP and the CVP, ratified in 1986, allows the SWP to purchase water from the CVP. Using conservation techniques and improving the efficiency of transfer might also increase water deliveries.

Operating rules for the reservoirs also could be modified to increase allowable reservoir storage in April, which would increase water storage at the end of the rainy season and deliverable water during the peak demand season in midsummer. However, an increase in water storage in the late winter and early spring is likely to reduce the amount of flood protection (increase the risk of flooding) in the region; this in itself could negatively affect owners of floodplain property. Floods also place the delta islands at risk because of higher water levels. The tradeoff between water supply and flood control in northern California represents a potentially serious policy conflict affecting all levels of government in the region. In fact, a meeting between representatives of the State DWR and Bureau of Reclamation, which was held to discuss Sheer and Randall's (Volume x) results, concluded that any likely changes in reservoir operation that would avoid a significant loss of flood safety would most likely bring about little improvement in the system's performance under the given climatic scenarios. Detailed study of this point is needed, however.

The second approach to maintain or increase water deliveries might be to construct new water management and storage facilities. However, trends over the past decade have shifted away from planning large storage facilities (e.g., the Auburn Dam and Delta Peripheral Canal). Building new facilities is expensive and raises serious environmental concerns such as development of wild and scenic rivers. Another option is to use smaller facilities, such as the proposed new off-stream storage facility south of the delta, and to improve the delta's pumping and conveyance facilities. With the help of these facilities, the SWP plans to achieve a 90% firm yield (the amount that can be delivered in 9 out of 10 years) of about 3.3 maf by 2010 (California Department of Water Resources, 1987a). Another relatively inexpensive option for off-line storage is artificial recharge of groundwater during wet years. The SWP is currently pursuing a proposal to deliver surplus water to groundwater recharge areas in the southern Central Valley to provide stored water for dry years.

The third approach to increase water deliveries is to turn to other sources of water. For instance, use of groundwater could be increased. However, in many metropolitan areas, groundwater bodies are currently being pumped at their sustainable yields. Any increase in pumping could result in overdraft. Furthermore, decisions to use groundwater are made by local agencies and/or individual property owners, and groundwater is not managed as part of an integrated regional water system. Whether to include it in the system is an important policy issue.

Another option is for southern California to choose to fully use its allotment of Colorado River water (which could lead to conflicts between California and other users of that water, especially Arizona). Other possibilities include desalinization plants, cloud seeding over the Sierras, and reuse of wastewater. However, desalinization plants are energy intensive and may exacerbate air quality problems. Also, cloud seeding is controversial, since downwind users may not be willing to lose some of their precipitation.

Options for Allocating Water Shortages

The second major policy question is how to best allocate potential water shortages. One way would be to allow greater flexibility in water marketing. The adverse effects of this policy change (e.g., perhaps water becoming too expensive for agriculture and possible speculative price increases) could be ameliorated through a variety of governmental policies. Yet, even with regulation, any changes in the current system along these lines would most likely be very controversial.

A second way to allocate the shortages is to rely on those mechanisms used in the past to deal with droughts and water shortages, specifically governmental restrictions on water use. In the past, these have included restrictions on "nonessential" uses of water (e.g., watering of lawns), increased use efficiency, and transfers of agricultural water to municipal and industrial uses. Increased efficiency of water usage through various conservation techniques could effectively increase the number of water users without actually increasing the amount of water delivered. If climate gradually changes and water shortages become more common, these restrictions could become essentially permanent.

Sacramento and San Joaquin River Delta

The delta area of the Sacramento and San Joaquin Rivers in the San Francisco Bay estuary receives great attention from governmental bodies at all levels because of its valuable agricultural land, its crucial role in the State's water resource system, and its sensitive environment. The results of the studies in this overall project suggest that this region could be significantly affected by climatic change. Major changes could occur in delta island land use and in the water quality of the San Francisco Bay estuary. The policy implications of these possible changes are discussed below.

Delta Island Land Use

A critical land use issue is whether to maintain the levees surrounding islands threatened by inundation. Much of the land present on these islands is below sea level and is usable for agriculture, recreation, and settlement only through levee protection.

The individual delta islands have a significant range of values. For example, some islands contain communities and highways, and others are strictly agricultural. The property value of the islands is about $2 billion (California Department of Water Resources, 1987b). The islands also help repel saline water from the delta pumping plants (see Figure 4-2).

The levees have been failing at an increasing rate in recent years, and further sea level rise could increase failure probability. Improving the levees to protect the islands from flooding at the existing sea level and flood probability would cost approximately $4 billion (California Department of Water Resources, 1982).

The issue of levee failure raises three important policy questions. First, will some or all of the levees be maintained? The range of options concerning the levees includes inaction, maintenance of the status quo, strategic inundation of particular islands, and construction of polder levees.

Inaction, meaning the levees are not improved with time, could eventually lead to the formation of a large brackish-water bay as all of the levees failed. Williams (Volume x) suggests that the area of the San Francisco Bay estuary could triple if all the levees failed.

Currently, the general policy is to maintain the delta's configuration. One important policy favoring the maintenance of the levees is the Delta Levee Maintenance Subventions Program, in which State financial assistance is available for maintaining and improving levees. The value of the islands for agriculture and maintenance of water quality (see below) has created additional institutional support for maintaining the levees, even though the cumulative cost may exceed the value of the land protected. Future funding decisions for this and related programs should consider the possibility of climate change. If the levees are maintained, an important policy question is who will pay for the maintenance.

Not all the islands are of equal value, especially with regard to their value in protecting the freshwater delivery system. A possible future policy response to rising sea level would be to maintain only certain levees and not reclaim other islands as they become flooded. In essence, this would be a strategic inundation policy. Some precedence exists for this policy, as Mildred Island was flooded in 1983 and not reclaimed; the high cost of reclaiming the island relative to its value was cited as a rationale.

Construction of large levees similar to the polders in Holland is an option for protecting the islands and maintaining shipping channels. However, this approach would be expensive and, though it has been discussed, has not attracted much serious attention.

Another policy question concerns failure of the levees. If all or some levees are allowed to fail, will landowners be compensated? If so, where will the money come from? The delta islands contain some of the most valuable agricultural land in the State. Loss of this land would be a severe economic hardship for the local farmers and for the associated business community. Whether these farmers should be compensated for their loss is an important public policy issue.

A final policy question concerns management of the delta islands. How will management of the delta islands be coordinated? Currently, four government bodies have jurisdiction over the islands at the local, State, and Federal levels. Coordination of these bodies will be required to reach decisions regarding the future of individual delta islands.

Water Quality of San Francisco Bay Estuary

The intrusion of saline waters into the upper reaches of the San Francisco Bay estuary could be a major problem in a warmer climate. Climate change is projected to cause increases in salinity in the estuary, largely as a result of sea level rise, levee failure, and the inadequacy of freshwater inflow to offset the increase in salinity. Furthermore, land subsidence due to groundwater extraction could augment sea level rise. In some areas of the estuary, subsidence up to 1.5 m (59 inches) has occurred within the recent past (Atwater et al., 1977).

Maintenance of current levels of salinity is addressed in the Water Rights Decision 1485 (D-1485) of 1978. This decision requires that water quality standards in the delta be maintained. If they are not, additional water must be released from reservoirs to improve the delta water quality, which could reduce the amount of water available for delivery. Current policy does not explicitly take into account the potential for future climate change. Thus, D-1485 could be interpreted as requiring maintenance of delta water quality standards even if sea level rises, causing further penetration of saline water into the Delta. Delta water quality standards are currently being reviewed at the Bay-Delta Hearing in Sacramento. This hearing began in mid-1987 and is expected to continue for 3 years. The choice of future options will be greatly affected by decisions made at the hearing.

Possible methods of combating the impacts of saltwater intrusion include maintaining levees, increasing freshwater outflows, reducing withdrawals, enlarging channels, constructing a barrier in the Carquinez Strait or lower delta, and/or constructing a canal around the delta's periphery. Alternatively, the freshwater pumping plants could be moved to less vulnerable sites. Decisions regarding response options will not be easily made. Levee maintenance and construction are costly. The water delivery agencies might be reluctant to increase delta outflows or reduce withdrawals. Enlargement of delta channels, construction of saltwater barriers, and construction of a peripheral canal are extremely controversial environmental issues. Another possible response to these climatic impacts would be a gradual, planned retreat from the delta, devoting resources to options compatible with the absence of a freshwater delta. This option would also be very controversial, both politically and environmentally.

Water Quality of Freshwater Systems

Water quality of lakes, streams, and rivers could change as climate changes. Results from the Castle Lake study indicate that primary production of subalpine lakes could increase, with the potential for changes in the water quality of mountain streams (Byron et al., Volume x). Reduction in summer flows of streams and rivers in the Central Valley Basin could concentrate pollutants in these aquatic systems. The major policy question relating to these potential changes is, "How will potential reductions in water quality below levels mandated in the current Water Quality Act of 1987 (Public Law 100-4) be prevented?"

Maintaining water quality despite decreased summer flows could be difficult and expensive. Controlling nonpoint source pollution is a goal of the Water Quality Act of 1987, and meeting this goal in the future could be more difficult and expensive because of the lower summer flows. Changes in land use near water courses to prevent runoff from agricultural land from reaching the water courses may be required. Reducing herbicide and pesticide use could also be another response, but this could harm agricultural production. Another option for preventing an increase in concentrations of pollutants in river reaches below reservoirs is to increase releases of reservoirs during summer months, which would dilute the pollutants. However, this strategy would have obvious negative impacts on water deliveries.

Municipalities located along rivers in the Central Valley Basin and that release treated sewage into them also could face increased difficulties in meeting water quality standards. Options include expanding sewage treatment facilities, which is expensive; releasing water from reservoirs to dilute the pollutants, as discussed above; or controlling the production of wastewater. Any municipalities planning for new sewage treatment plants should include climatic change as one factor in the design criteria.

Reductions in summer flows could harm populations of aquatic organisms and terrestrial organisms that use riparian habitats. To the extent that these species become threatened with extinction, laws requiring preservation of endangered species (e.g., Endangered Species Act of 1973) may be invoked as a legal basis for increasing reservoir releases to preserve these species. This could place into conflict the governmental agencies and public constituencies concerned with preservation of biodiversity and those concerned with economic impacts on agriculture and industry.

Terrestrial Vegetation and Wildlife

Changing species composition and productivity might alter the character of forestry operations and the aesthetic appeal of currently popular recreational areas. Climate-induced reductions in growth and regeneration rates, and increases in losses from wildfire and insect damage and mortality, could decrease the size and value of industrial forests in the State. How these changes will be managed is a complex question involving all levels of government as well as private landowners.

One major step in response to possible future climatic change is to incorporate climate considerations into current planning processes. The Forestry chapter of this report discusses Federal planning for effects of climate change on forests. Similar planning changes could be made at other levels of government. Coordinating the actions of government agencies involved with land management to climatic change in California is another possible response.

The flora and fauna in California are highly diverse and include many rare and endangered species. Climate could change faster than some species could adapt, leading to local extinction of these species. Species conservation (as mandated by the Rare and Endangered Species Act of 1973) might require habitat reconstruction and/or transplanting in some situations. Monitoring programs may need to be instituted to track trends in populations and communities. Extensive programs have been developed for currently endangered species in the State (e.g., the California condor), and similar efforts would probably be mounted in the future for other highly valued species.

Agriculture

Changes in water availability and temperature stresses are projected to affect agricultural production. How will changes in agricultural production and crop types be managed, and how will California agriculture respond in national and international settings? (See the Agriculture chapter of this report for further discussion.)

Historically, agriculture has quickly adapted to climatic fluctuations. New technology and reallocation of resources might offset the impact of changed climatic conditions and water availability. Improved farm irrigation efficiency, such as extensive use of drip irrigation, could mitigate the impact of water delivery shortages. Water marketing may provide a cost-effective means of meeting water demands and providing market opportunities for conserving water (Howitt et al., 1980). For example, water marketing may provide rights holders with the financial ability to invest in water conservation programs to cope with the impacts of climatic warming on water availability.

Changes in cropping locations and patterns of water use could exacerbate nonpoint source pollution and accelerated rates of groundwater overdraft. Further, changing water supply demands may heighten the conflicts between water allocation strategies and ecosystem and wildlife values.

It is uncertain how agricultural effects would be manifest in California's evolving economic and policy environment. For example, increased commodity prices could mitigate financial impacts of potential reductions in crop acreage and production.

Wetland Vegetation and Fisheries

Wetland species are valuable ecologically, aesthetically, and economically (photography, hunting, fishing, etc.). With rising sea level, areas supporting shallow water vegetation might be inundated and converted to deep-water habitats supporting different species. New shallow-water sites could be created by artificially adding sediment. This option features its own environmental impacts and would most likely be expensive. However, maintaining shallow-water vegetation is important not only to the conservation of plant species but also to migratory birds, which feed on such vegetation.

Salinity impacts on phytoplankton and fisheries might be controlled via levee maintenance coupled with increases in delta outflow.

Shoreline Impacts of Sea Level Rise

The California coast includes a diverse array of shorelines ranging from cliffs to sandy beaches. Erosion along these coastlines may increase as a consequence of sea level rise. Such erosion could substantially damage shoreline structures and recreational values, and preventing the erosion would be very costly. For example, protecting the sewer culvert of the San Francisco Westside Transport Project from potential damage caused by sea level rise may cost over $70 million (Wilcoxen, 1986). Sound planning for shoreline structures should consider future erosion that may be caused by sea level rise. (See Sea Level Rise chapter for further discussion of these issues.)

The accumulation of sediment behind water project dams and the effects of diversion structures, dredging operations, and harbor developments have limited the source of sediment for beach maintenance (particularly along the southern California coast). Individual landowners and institutions constructing such structures should consider their effects on sedimentation processes. Only through artificial deposition of sand (primarily from offshore sources) have southern Californian beaches been maintained. Beaches provide recreational areas and storm buffers, and their maintenance will require a major and continued commitment.

Air Quality

Increasing temperatures could exacerbate air pollution problems in California, causing an increase in number of days in which pollutant levels are higher than National Ambient Air Quality Standards. Devising technological and regulatory approaches to meet ambient air standards is currently a major challenge in certain regions of the state and these efforts must be continued. In the future, meeting air quality standards may become even more difficult to achieve under a warmer climate. Policy makers such as EPA and the California Air Quality Board may wish to consider possible climatic changes as they formulate long-term management options for improving air quality, to ensure air quality standards are met under warmer conditions.

Energy Demand

A warmer climate could affect both energy demand and supply. For instance, higher temperatures could cause increased cooling demands, and changes in runoff could affect hydroelectric power generation. Consequently, institutions in California that are involved with energy planning, such as the State Energy Resources Conservation and Development Commission, should begin to consider climate change in their planning efforts so that future energy demands can be met in a timely and efficient fashion.

REFERENCES

Atwater, B.F., C.W. Hedel, and E.J. Helley. 1977. Late Quaternary Depositional History, Holocene Sea Level Changes, and Vertical Crustal Movement, Southern San Francisco Bay. U.S. Geological Survey Professional Paper 1014. Menlo Park, CA: U.S. Geological Survey.

Atwater, B.F., S.G. Conard, J.N. Dowden, C.W. Hedel, R.L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. In: Conomos, T.J., ed. San Francisco Bay: The Urbanized Estuary. San Francisco, CA: Pacific Division, American Association for the Advancement of Science, pp. 347-386.

Barbour, M.G., and J. Major. 1977. Terrestrial Vegetation of California. New York: John Wiley and Sons.

Budyko, Mi.I. 1982. The Earth's Climate: Past and Future. New York: Academic Press.

California Department of Water Resources. 1982. Delta Levees Investigation. Bulletin 199. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1983. The California Water Plan: Projected Use and Available Water Supplies to 2010. Bulletin 160-83. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1985. California State Water Project. Typewritten brief. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1986. Operations Criteria Applied in DWR Planning Simulation Model. Memorandum report. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1987a. California Water: Looking to the Future. Bulletin 160-87. Sacramento, CA: California Department of Water Resources.

California Department of Water Resources. 1987b. Sacramento-San Joaquin Delta Atlas. Sacramento, CA: California Department of Water Resources.

California Division of Forestry and Fire Protection. 1988. California's Forest and Rangelands: Growing Conflict Over Changing Uses. Sacramento, CA: Forest and Rangeland Resources Assessment and Policy Act Committee.

Conomos, T.J., R.S. Smith, and J.W. Gartner. 1985. Environmental Setting of San Francisco Bay. Hydrobiologia 129:1-12.

Davis, O.K., J.C. Sheppard, and S. Robertson. 1986. Contrasting climatic histories for the Snake River Plain result from multiple thermal maxima. Quaternary Research 26:321-339.

Denton, R.A., and J.R. Hunt. 1986. Currents in San Francisco Bay. Final report. Berkeley, CA: University of California.

Doorenbos, J., and A.H. Kassam. 1979. Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. Rome: FAO.

Fernald, M.L. 1950. Gray's Manual of Botany, 8th ed. New York: American Book Co.

Fischer, H.B. 1970. A Method for Predicting Pollutant Transport in Tidal Waters. Contribution No. 132. Berkeley, CA: University of California Water Resources Center.

Gleick, P.H. 1987a. Regional hydrologic consequences of increases in atmospheric CO_2 and other trace gases. Climatic Change 10:137-161.

Gleick, P.H. 1987b. The development and testing of a water balance model for climate impact assessment: modeling the Sacramento Basin. Water Resources Research 23:1049-1061.

Goldman, C.R., A. Jassby, and T. Powell. 1989. Interannual fluctuations in primary production: impact of climate and weather at two subalpine lakes. Limnology and Oceanography, In press.

Howitt, R.E., D.E. Mann, and H.J. Vaux Jr. 1980. The economics of water allocation. In: Englebert, E.A., ed. Competition for California Water. Berkeley, CA: University of California Press.

Howitt, R.E., and P. Mean. 1985. Positive Quadratic Programming Models. Working Paper No. 85-10. Department of Agricultural Economics, University of California, Davis.

Kjeldson, M.A., P.F. Raquel, and F.W. Fisher. 1981. Influences of freshwater flow on chinook salmon in the Sacramento-San Joaquin Estuary. In: Cross, R.D., and Williams, D.L., eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries, Vol. 2. Washington, DC: U.S. Department of the Interior, pp. 88-108.

Leverenz, J.W., and D.J. Lev. 1987. Effects of carbon dioxide-induced climate changes on the natural ranges of six major commercial tree species in the western United States. In: Shands, W.E., and J.S. Hoffman, eds. The Greenhouse Effect, Climate Change, and U.S. Forests. Washington, DC: The Conservation Foundation, pp. 123-155.

Macdonald, K.B. 1977. Coastal salt marsh. In: Barbour, M.G., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley & Sons, pp. 263-294.

Major, J. 1977. California climate in relation to vegetation. In: Barbour, M.J., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley & Sons, pp. 11-74.

Meyer, P.A. 1987. The value of wildlife in San Francisco Bay. Exhibit 38, entered by the Bay Institute of San Francisco to the State Water Resources Control Board in Sacramento, CA.

Miller, C.S., and R.S. Hyslop. 1983. California: The Geography of Diversity. Palo Alto, CA: Mayfield.

Munz, P.A., and D.D. Keck. 1959. A California Flora. Berkeley, CA: University of California Press.

Nichols, D.R., and N.A. Wright. 1971. Preliminary map of historic margins of marshland, San Francisco, California. U.S. Geological Survey Open File Map, San Francisco Bay Region Environment and Resource Planning Study. Basic Data Contribution 9.

Raven, P.H. 1977. The California flora. In: Barbour, M.G., and J. Major, eds. Terrestrial Vegetation of California. New York: John Wiley & Sons, pp. 109-137.

Ritchie, J.C., L.C. Cwynar, and R.W. Spear. 1983 Evidence from north-west Canada for an early Holocene Milankovitch thermal maximum. Nature 305:126-128.

Sheer, D.P., and M.L. Baeck. 1987. Documentation of the CVP/SWP Simulation Models Developed by WRMI. Columbia, MD: Water Resources Management, Inc.

Sudman, R.S. 1987. Layperson's Guide to the Delta. Sacramento, CA: Western Water Education Foundation.

U.S. Bureau of Reclamation. 1985. Summary Statistics, 1984; Volume 1: Water, Land and Related Data. Denver, CO: U.S. Bureau of Reclamation, Division of Water and Land Technical Services.

U.S. Department of Agriculture. 1987. Agricultural Statistics 1987. Washington, DC: U.S. Government Printing Office.

U.S. Department of the Interior. 1986. National Forest Statement of Receipts, Fiscal Year 1986. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. In prep. Ecological Effects of Global Climatic Change. Chapter 5. In: U.S. EPA Global Climatic Change Program.

U.S. Maritime Administration. 1985. Containerized cargo statistics, 1983. Washington, DC: Government Printing Office.

Wilcoxen, P.J. 1986. Coastal erosion and sea level rise: implications for ocean beach and San Francisco's Westside Transport Project. Coastal Zone Management Journal 14:173-191.

DRAFT

CHAPTER 5

GREAT LAKES

FINDINGS

Global climate change could affect the Great Lakes by lowering lake levels, reducing the ice cover, degrading water quality in rivers and shallow areas of the lakes. It could also expand agriculture in the north, change forest composition, decrease regional forest productivity in some areas, increase open water fish productivity, and alter energy demand and supply.

Lakes

- Average lake levels could fall by one-half to two and one-half meters because of higher temperatures under the scenarios in this report. A drop of one meter would leave average levels below historic lows. Even if rainfall increases, the levels would fall because increased temperatures reduce the snowpack and accelerate evaporation. The estimates of lake level drop are sensitive to assumptions about evaporation; under certain limited conditions, lake levels could rise.

- As a result of higher temperatures, the duration of ice cover on the lakes would be reduced by one to three months. Ice would still form in near-shore and shallow areas. Changes in wind speed and storm intensity would affect the duration of ice cover.

- Shoreline communities would have to make adjustments to lower lake levels over the next century. Hundreds of millions of dollars would have to be spent along the Illinois shoreline along, dredging ports, harbors, and channels to greater depths than without climate change. Water intake and outflow pipes may have to be relocated. On the other hand, lower levels would expose more beaches, which would enhance shoreline protection and recreation.

- Climate change could have both good and bad effects on shipping. Lower lake levels would necessitate increased dredging of ports and channels or reduced cargo loads. Without dredging, shipping costs could rise 2 to 33 percent due to a reduction in cargo capacity. However, reduced ice cover would lengthen the shipping season and would sufficiently compensate for lower lake levels up to a drop of several meters.

Water Quality and Fisheries

- Higher temperatures would change the thermal structure of the Great Lakes. The result would be a longer and greater stratification of the lakes and increased growth of algae. These two factors would combine to reduce dissolved oxygen levels in shallow areas of lakes such as Lake Erie. A study of southern Lake Michigan found that annual turnover of the lakes could be disrupted.

- Climate change could increase concentrations of pollutants in the Great Lakes Basin. Dredging of ports could suspend toxic sediments in near-shore areas. Potential reductions in river flow in the Basin would create higher concentrations of pollutants in streams. The disposal of toxic dredge spoils was not studied in this report.

- The effects on fisheries would be miked. Higher temperatures may expand fish habitats during fall, winter, and spring and accelerate the growth and productivity of open water fish such as bass, lake trout, and pike. On the other hand, fish populations could be hurt by decreased summer habitats, lower summer dissolved oxygen levels and by potential loss of wetlands due to dropping lake levels. The effects of loss of wetlands, reductions in ice cover, introduction of new exotic species, and increase in species interaction were not analyzed.

Forests

- The composition and abundance of forests in the Great Lakes region will change. Higher temperatures and lower soil moisture could reduce forest biomass in dry sites in central Michigan by 77 to 99 percent. These mixed hardwood and oak forests would become oak savannas or grasslands. In northern areas such as Minnesota, boreal and cedar bog forests could change to treeless bogs, and mixed northern hardwood and boreal forestry in upland areas would become all northern hardwoods. Productivity could decrease on dry sites and bogland sites, but increase on some well drained wet sites. Softwood species that are currently commercially important could be eliminated and replaced by hardwood, such as oak and maple, which are useful for different purposes.

- Depending on the scenario, declines in forests could be evident in 30 to 60 years. These results do not reflect additional stresses, such as acid rain and oxidant levels, nor do they reflect the possible beneficial impacts of increased CO_2 levels.

Agriculture

- Considering climate change alone, corn and soybean yields in northern areas, such as Minnesota, could increase by 50 to 100 percent and would decline in the rest of the region by up to 60 percent. The combined effects of climate and CO_2 could further increase yields in the North, and would result in net increases in the rest of the region, unless climate change is severe.

- Agricultural production in the northern part of the region could expand as a result of declines elsewhere. Acreage in the Corn Belt states may change little. However, the presence of glaciated soils in the North could limit this expansion. Wider cultivation in the north could increase erosion and runoff, and degrade surface and groundwater quality. Increased agriculture would require changes in the infrastructure base, such as transportation networks.

Electricity Demand

- There would be little net change in annual electricity demand. In northern areas, such as Michigan, reduced heating needs would exceed increased cooling requirements, while in southern areas, such as Illinois, cooling needs would be greater than heating reductions. The annual demand for electricity in the entire region could rise by 1 to 2 billion kilowatt hours by 2010 and by 8 to 17 BKWH (less than 1%) by 2055. This study did not analyze the reduced use of other fuels such as oil and gas in the winter, changes in demand due to higher prices, and the impacts on hydroelectric supplies. Previous studies have suggested that reduced lake levels and river flows would lead to reductions in these supplies.

- By 2010, approximately 3 to 8 gigawatts would be needed to meet the increased demand, and by 2055, 23 to 48 GW would be needed -- an 8 to 11 percent increase over baseline additions that may be needed without climate change. These additions would cost $23 to 35 billion by 2055.

Policy Implications

- U.S. and Canadian policy makers, though such institutions as the International Joint Commission and other institutions, should consider the implications of many issues for the region. This study raises additional issues concerning:

- -- The water regulation plans for Lake Ontario and possibly for Lake Superior lake levels.
- -- The potential increased demands for diverting Great Lakes water for uses outside of the basin. Before such a potential demand could be accommodated, additional analysis would be required. This is not currently allowed by federal statutes.
- -- Long range industrial, municipal, and agricultural water pollution control strategies will be affected by climate change. Agencies such as EPA may wish to examine the implications for long-term point and nonpoint water pollution control strategies.
- -- The research, planting, and land purchase decisions in northern forests supported research by federal, state, and private institutions.

CLIMATE-SENSITIVE NATURAL RESOURCES IN THE GREAT LAKES REGION

The Great Lakes region* is highly developed, largely because of its natural resources. The steel industry developed along the southern rim of the lakes, in part because iron ore from the north could be inexpensively transported over the lakes. Rich soils, moderate temperatures, and abundant rainfall have made the southern part of the region a major agricultural producer. Forests are abundant in the north and support commercial and recreational uses. The basin has become the home of over 29 million Americans and produces 37% of U.S. manufacturing output. (U.S. EPA, 1987; Ray et al.). Although these resources provide many benefits, they are also quite vulnerable to climate changes, oftentimes with negative impacts upon society.

Current Climate

The Great Lakes region has a mid-latitude continental climate. Winter is sufficiently cold to produce a stable snow cover on land and ice on the lakes. Average January temperatures over Lake Superior are -15°C (5°F), and the average July temperatures in the southern part of the region are 22°C (72°F). The average rainfall varies from 700 to 1,000 mm (27 to 39 inches), depending on location (Cohen, in Glantz Volume _).

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*This chapter will cover only the U.S. side of the Great Lakes and the eight States bordering on them (see Figure 5-1).

The Lakes

The Great Lakes are a system of five major lakes that contain approximately 18% of the world supply of freshwater and 95% of the freshwater in the United States (U.S. EPA and Environment Canada, 1987) (see Figure 5-1, Map of Great Lakes). The natural flow of the lake system begins in Lake Superior, the largest of the lakes, which drains via the St. Marys River into Lakes Michigan and Huron.* Water from Lakes Michigan and Huron flows out through the St. Clair River into Lake St. Clair. From there, the water flows through the Detroit River and into Lake Erie, the shallowest lake. The Niagara River connects Lakes Erie and Ontario, and the system ultimately empties into the Atlantic Ocean via the St. Lawrence River and Seaway.

The greatest influence on lake levels is nature. Seasonal fluctuations are on the order of 0.3-0.5 m, with the lakes peaking in late summer because of condensation over the northern lakes and reaching minimum levels in late winter. Interannual lake level changes have been much larger, approximately 2 m.

Lake Regulation

The flow between the lakes is controlled by dams at two points: (1) the St. Mary's River to control levels of Lake Superior; and (2) Iroquois, Ontario, to control Lake Ontario. The major diversion out of the lakes is the Chicago diversion, which transfers water from Lake Michigan through the Illinois River into the Mississippi River. Man's influence on lake levels is relatively small. Doubling the flow down the Chicago diversion would lower lake levels only by 2.5 inches in 15 years (Quinn, 1987).Joint control of lake supply was codified in the Boundary Waters Treaty of 1909 between Canada and the United States, which created the International Joint Commission (IJC) consisting of representatives from both countries. The IJC regulates flow through the control structures and diversions by balancing the needs of shipping, hydropower, and consumptive uses among the lakes and along the St. Lawrence River and Seaway. Two regulatory plans (Plan 1977 for Superior and Plan 1958D for Ontario) set ranges of levels between which Lakes Superior and

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*Considering a single hydrologic unit because they are connected by the Straights of Mackinac.

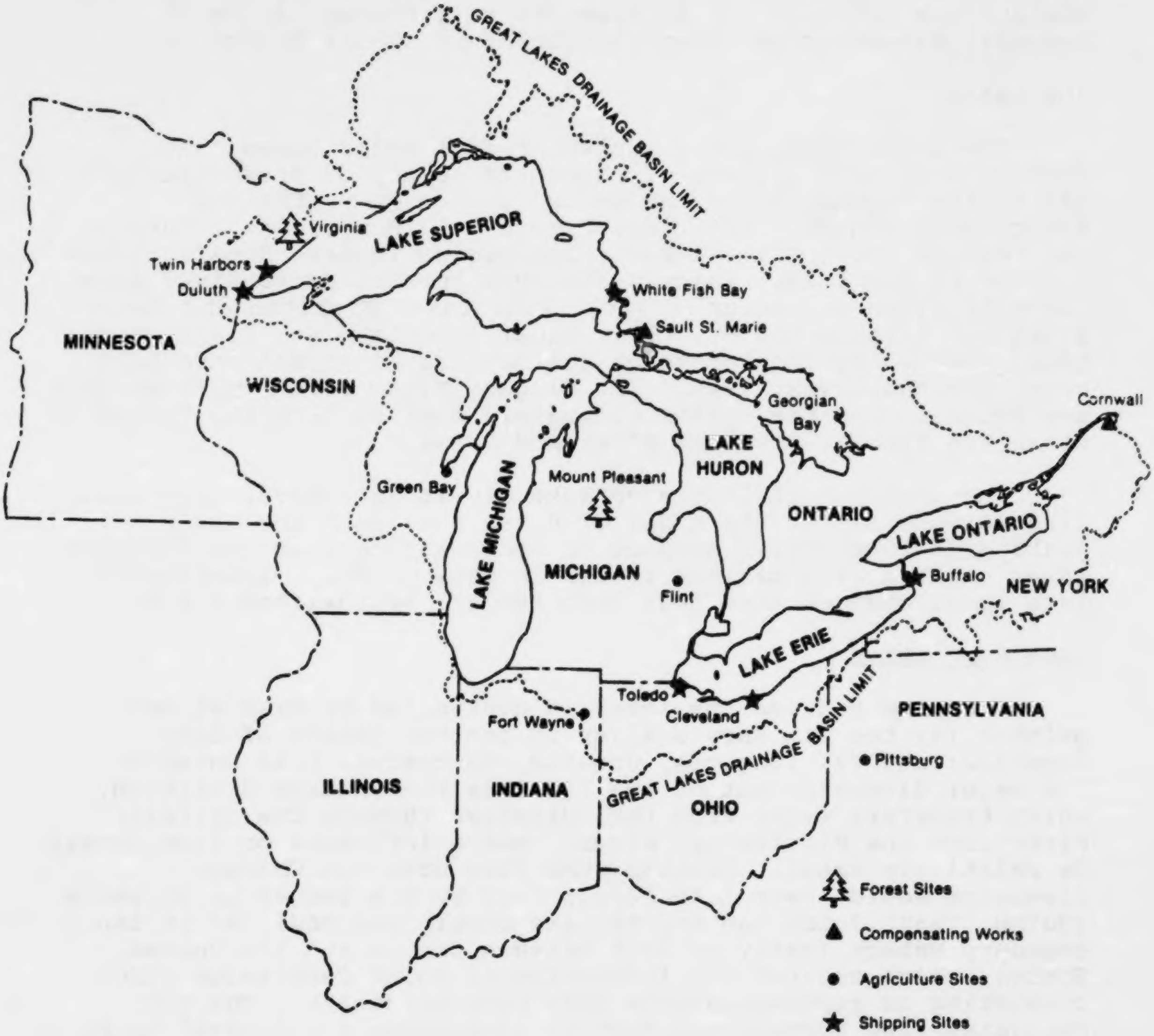
GREAT LAKES DRAINAGE BASIN LIMIT
MINNESOTA
WISCONSIN
Virginia
Twin Harbors
Duluth
LAKE SUPERIOR
White Fish Bay
Sault St. Marie
Georgian Bay
Cornwall
LAKE HURON
Green Bay
Mount Pleasant
LAKE MICHIGAN
MICHIGAN
Flint
ONTARIO
LAKE ONTARIO
Buffalo
NEW YORK
LAKE ERIE
Toledo
Cleveland
PENNSYLVANIA
Fort Wayne
Pittsburg
ILLINOIS
INDIANA
GREAT LAKES DRAINAGE BASIN LIMIT
OHIO
Forest Sites
Compensating Works
Agriculture Sites
Shipping Sites

Figure 5-1. Map of the Great Lakes studies.

Ontario must be maintained. Diversion out of the lakes is also limited by law. Flow through the Chicago diversion was limited by the Supreme Court to 90 m^3/s (3,200 ft^3/s) (Tarlock, 1988), and the 1986 Water Resources Development Act forbids diversion out of the lakes' basin without the consent of all Great Lakes governors (Ray et al.).

Climate-Sensitive Uses of the Lakes

Shipping

The U.S. Great Lakes fleet, which consists of approximately 70 ships, transported over 171 million tons of cargo in 1987 (New York Times). The tonnage of U.S. shipping consists of iron ore, coal, and limestone, all primary inputs for steel (77%); lake grain (13%); and petroleum products, potash, and cement (10%) (Nekvasil, 1988) Cargo volumes are displayed in Table 5-1. Most of the goods are shipped within the Great Lakes, with only 7% of the tonnage (mainly grains) shipped to overseas markets (Ray et al.). Although shipping activity had declined as a result of reductions in U.S. steel production, recent increases in steel output have lead to additional demand for shipping (Agar, 1987; New York Times).

Great Lakes ships last over half a century and are designed to pass within a foot of the bottom of channels and locks. Cargo capacity is quite sensitive to lake and channel depth because of this low clearance. The presence of ice usually shuts down Great Lakes shipping up to 4 months each year.

Table 5-1. Cargo for U.S. Great Lakes Shipping in 1987 (thousands of tons)

Cargo	Weight
Iron Ore	61,670
Coal	37,731
Stone	33,164
Grain	22,338
Petroleum Products	11,491
Cement	3,806
Potash	1,702
Total	171,902

Source: Nekvasil (1988).

Hydropower

The eight Great Lakes States use the connecting channels and the St. Lawrence River to obtain 35,435 gigawatt hours of hydropower each year, which is about 5% of their electricity generation. About four-fifths of the hydropower is produced in New York State, which derives over 26% of its electricity from hydropower (Edison Electric Institute, 1987).

Municipal Consumption

Most water used for the domestic and industrial consumption in the basin is taken from the lakes. Surface waters supply 95% of the basin's water needs. By the year 2000, consumption is estimated to increase by 50 to 96% (Ray et al.; IJC, 1985).

Fisheries

In 1984, the value of the harvest to the U.S. commercial fishing industry was approximately $15 million (U.S. EPA and Environment Canada, 1987; Statistical Abstract of the United States, 1987). Although most fishing in the Great Lakes is for recreation, fisheries are managed by the States, although the Great Lakes Fishery Commission coordinates activities among the States.

Tourism

Three National and 67 State parks are located along the shores of the lakes, as are numerous local parks. Over 63 million people visited these parks in 1983. (Ray et al.; Great Lakes Basin Commission, 1975). In 1984, lake-generated recreation produced $8 to 15 million in revenues. Fishing, boating and swimming are very popular.

Shoreline Development

Over 80% of the U.S. side of the Great Lakes shoreline is privately owned. One of the most developed shorelines is the 101-km Illinois shoreline, where many parks and residential buildings, including apartment houses, are built near the water's edge. Shoreline property owners have riparian rights to use adjoining waters. The shoreline property owners cannot substantially diminish the quantity or quality of surface waters (Ray et al.).

Climate and Water Quality

Water quality is directly affected by climate. Lower stream runoff increases concentrations of pollutants. Every summer, the lakes stratify into a warmer upper layer and a cooler lower layer. This stratification can limit biological activity by restricting the flow of nutrients between layers. In addition, warm temperatures and an excess supply of nutrients (phosphorous and other chemicals from agricultural runoff and sewage effluent) can lead to algal blooms which decay and cause a loss of oxygen (eutrophication) and reduction in aquatic life in the lower layers of lakes such as Lake Erie. Cool weather and the formation of ice help to deepen the mixed layer and break up the stratification and thoroughly mix the lakes in the winter.

Development, industrialization, and intensive agriculture in the Great Lakes Basin has created serious pollution in the lakes, especially Lake Erie. In the early 1970s, nutrient loadings were so high that Lake Erie experienced significant eutrophication problems for several years (DiToro, 1987).

Two measures have helped improve water quality. The U.S.-Canada Great Lakes Water Quality Agreement of 1972 called for controlling nutrient inputs and eliminating the discharge of toxic chemicals, and the Clean Water Act mandated construction of sewage treatment plants and controls on industrial pollutants. The United States and Canada spent a total of $6.8 billion on sewage treatment in the Great Lakes. By 1980, nutrient loadings into Lake Erie had been cut in half (Ray et al.; DiToro, 1987), and water quality had markedly improved.

Fluctuating Lake Levels

Recent high and low lake levels have significantly affected users of the lakes. In 1964, Lake Michigan was 0.92 m below average, making some docks and harbors unusable. Shipping loads were reduced by 5 to 10% and more shipments were required, subsequently raising the cost of raw materials and supplies by 10 to 15%. In addition, many water intakes had to be extended or lowered (Changnon). Flow through the Niagara hydropower project fell by more than 20%, with electricity generation off by more than 35%. Flow through New York's St. Lawrence hydro project was more than 30% below its mean, with electricity generation decreased by 20% (Linder, 1985). Low lake levels also provide benefits: as beaches have become enlarged, their use and enjoyment have increased.

The low water levels in the 1960s exposed the supporting structures along Chicago's shoreline to air, causing dry rot. When lake levels rose to record height in the 1980s, the wood pilings and sections of the revetment collapsed. Apartment houses that were built too close to the shoreline during the low levels of the 1960s were flooded, as were roadways built close to the shore. The estimated construction cost for rebuilding the damaged shoreline protection system is $843 million (Changnon). The last 2 years have been relatively hot and dry, causing lake levels to recede to average levels. The lower levels have forced shippers to reduce tonnage just as the steel industry in the region is undergoing a resurgence.

Land Around the Lakes

The land in the Great Lakes region is extensively used for industry, agriculture, and forestry. Many of the uses are sensitive to climate.

Land Uses

Urban Development

Approximately 29 million people live in the Great Lakes Basin, mostly in the urban areas around the cities on the southern edge of the Great Lakes: Chicago, Detroit, Cleveland, Toledo, and Buffalo. Many of the residents work in manufacturing industries, which despite recent declines, still provide 23% of payroll employment (Ray et al.).

Agriculture

Agriculture is the single largest user of land: 42% of all land in the eight Great Lakes States is devoted to crops, and an additional 10% is used for pasture. The Great Lakes States encompass most of the Corn Belt. In 1983, roughly 59% of all U.S. cash receipts for corn and 40% of the receipts for soybeans came from this region. Overall, the Great Lakes States produced 26% of the total U.S. agriculture output, or $36 billion. (Federal Reserve Bank of Chicago, 1985). Most crops are grown on dryland as only about 1% of the region's croplands were irrigated in 1975 (U.S. Department of Commerce, 1987).

Livestock are also important to the agricultural economy of the region. Approximately 18% of U.S. cattle are raised in these eight States; of these, 52% are dairy cows (USDA, 1987). (The sensitivity of livestock to climate change is discussed in the Agriculture chapter of this report.)

Forests

The forests in the region have commercial, recreational, and conservation uses. The forests in the south are mainly oak and northern hardwoods, such as maple. The north has almost 21 million hectares (ha), (52 million acres), of forests consisting mostly of northern hardwoods, such as maple, birch, and beech, and boreal forests, such as spruce and fir trees. The Federal and State governments own, respectively, 11 and 13% of the forests in Michigan, Minnesota, and Wisconsin; while over half are privately owned (USDA, 1982). The pulp, construction, and furniture industries are major consumers of such species as aspen, pines, balsam fir, spruce, maples, paper birch, and oak. The forest industry is a major employer in the northern part of the region. In Wisconsin, for example, 283,000 jobs are in timber harvesting and manufacturing related to forestry (Botkin; USEPA and Environment Canada, 1987). Forestry is considered to be a growht industry in the region as Michigan has identified forest products as one of the three key industries targeted for expansion in the State (Ray et al.).

PREVIOUS CLIMATE CHANGE STUDIES

The impacts of climate change on many of the systems in the Great Lakes have been analyzed in separate and unrelated studies. Canadian researchers have examined the potential impacts of climate change on Great Lakes levels and have concluded that levels would fall. Cohen (1986) used hydrologic calculations to estimate that the lakes might fall between 0.2 and 0.8 m. More recently, Sanderson (1988) used a hydrologic model of the lakes also to estimate that the lakes would drop by an average of 0.2 to 0.6 m. Wall (1985) concluded that lower lake levels could reduce ecological diversity and dry up enclosed marshes. In another study, Cohen (1987) estimated that withdrawals of water from the lakes for municipal consumption would increase by about 2.5% on an annual basis and would only marginally affect lake levels.

Assel et al. (1985) studied the extent of ice cover during the winter of 1982-83, which had temperatures 3.3-4.4°C warmer than the 30-year mean. They found that ice cover on Lake Superior was reduced from a normal 75% coverage to 21%. On Lake Erie, ice coverage was down to 25% from the normal 90%. Meisner et al. (1987) conducted a literature review on the possible effects of global warming on Great Lakes fish. Results are discussed in the fisheries section of this chapter.

Linder (1987) used the GISS transient to estimate impacts on electricity demand and hydropower generation in 2015 in upstate New York. He found total energy demand declining by 0.21-0.27%, but peak demand increasing by 1-2%. Meanwhile, hydropower production could decline between 6 and 8.5% owing to reductions in streamflow.

Impacts on managed and un-managed vegetation have also been studied. The Land Evaluation Group examined the potential impacts of climate change on agriculture in Ontario and found that yields could decrease in southern Ontario and farming could become feasible in northern Ontario. The study also indicated that the direction of change for yields depends on whether rainfall increases or decreases (Land Evaluation Group, 1986). Solomon and West (1986) used a stand simulation model (see forest section of the chapter) to estimate impacts of doubling and quadrupling of CO_2 levels on a northwest Michigan coniferous-deciduous transitional forest. They found that doubled CO_2 would lead to an eventual disappearance of boreal forests and an increase in deciduous trees. Total biomass would decline at first and rebound in about two centuries.

Two studies by Canadian researchers examined the possible impacts of climate change on tourism and recreation in Ontario. Both studies used climate change scenarios based on the GISS and GFDL models (although these may have been earlier model runs). Crowe (1985) estimated that snowfall would decrease by 25-75%, and the ski season in southern Ontario would be cut by 75-92% (7-12 weeks) and 13-31% (2-4 weeks) in the north. Wall found similar results. He concluded that reduced snowfall could eliminate skiing in southern Ontario and would shorten the northern Ontario ski season by 30-44%. A longer summer season could increase such summer tourism activities as camping. Wall (1985) also thought that lower lake levels could decrease ecological diversity and dry up enclosed marshes.

GREAT LAKES STUDIES IN THIS REPORT

Unlike previous studies, the studies for this report used common scenarios to address some of the potential impacts of climate change on a number of natural and societal systems in the Great Lakes region. The studies address the direct effects of climate change on the resources and some of the indirect effects on infrastructure and society. They focused on the lakes themselves, examining such issues as lake levels, ice cover, thermal structure, and fisheries. They also looked at the effects of these changes on shipping and shoreline properties, and examined the sensitivities of agriculture and forest to climate change. Finally, the studies examined the implications of climate change for Great Lakes policies and institutions. Some of the studies were linked quantitatively, but most were conducted independently of each other.

The studies involved either new topics or approaches that were not used in previous studies. For example, the analysis of lake levels used a more complex hydrologic model than was used previously. The agriculture analysis complements the Land Evaluation Group's study of Ontario by using a different model to examine impacts on the U.S. side of the lakes. The potential impacts of climate change on thermal structure were examined for the first time. Also for the first time, models were used to analyze impacts on fisheries. This study complements previous studies on forests by using a combination of modeling techniques to test the similarity of results.

The following analyses were performed for this report:

Direct Effects on Lakes

- o Lake Levels - Croley and Hartmann, Great Lakes Environmental Research Laboratory.
- o Ice Cover - Assel, Great Lakes Environmental Research Laboratory.

Impacts of Lake Changes on Infrastructure

The results from the first two studies were used in the following studies:

- o Great Lakes Shipping - Keith, DeAvila, and Willis, Engineering Computer Optecnomics, Inc.
- o The Impacts of Low Lake Levels on the Illinois Shoreline - Changnon, Leffler and Shealy, Illinois State Water Survey.

Water Quality

The following studies concern water quality and the effects on aquatic life in the lakes. The first two studies examined the direct effects of climate on the thermal structure of some of the lakes.

- o Thermal Structure of Southern Lake Michigan - McCormick, Great Lakes Environmental Research Laboratory.
- o Eutrophication of the Central Basin of Lake Erie - Blumberg and DiToro, Hydroqual, Inc.

The results from these studies were used in the following:

- o Great Lakes Fisheries - Magnuson, Regier, Sheeter, Hill, Holmes, and Meisner, Universities of Wisconsin and Toronto.

Forests

A series of studies on forests was commissioned to examine shifts in ranges, transient impacts, and the potential for migration of some Great Lakes forests. Basically, these are different analytic techniques for understanding how climate change may affect the composition and abundance of forests in the region.

- o Transient Effects on Great Lakes Forests - Botkin, Nisbet, and Reynales, University of California at Santa Barbara.
- o Forest Migration - Zabinski and Davis, University of Minnesota.
- o Ecological Response Surfaces - Overpeck and Bartlein, Lamont-Doherty. (Regional results will be taken from this study.)

Agriculture

The potential changes in agriculture in the Great Lakes were analyzed by studying changes in crop yields in the region and integrating the results in a national analysis of production changes. That national analysis was used to determine if production in the region could increase or decrease. The results of these studies were used to examine potential farm level adjustments.

- o Crop Yields in Great Lakes States - Ritchie, Baer, and Chou, Michigan State University.
- o Farm Level Adjustments by Illinois Corn Producers - Easterling, Illinois State Water Survey.

This chapter will use regional results from the following:

- o Economics Effects on Agriculture - Adams, Glyer and McCarl, Oregon State University.

Energy

This project analyzed potential changes in the national demand for electricity and estimated changes in regional demands. Results for the Great Lakes region are presented in this chapter.

- o Electric Utilities - Linder and Inglis, ICF, Inc.

Policy

The potential policy implications of the changes indicated by these and previous studies for local, State, Federal, and international decisionmaking are examined. This project provided information for the background and policy implications sections. Results are not presented as part of the results section.

- o The Implications for Policies and Institutions - Ray, Brah, and Lindland, The Center for the Great Lakes.

GREAT LAKES REGIONAL SCENARIOS

All three GCMs that provide the basis for the climate change scenarios show rather large increases in temperature for the Great Lakes region under the doubled CO_2 climate. The seasonal and annual temperatures and precipitation are displayed in Figure 5-2. The OSU scenario has an annual temperature rise of 3.5°C, with no change in seasonal pattern. The GISS scenario is about a degree warmer on average and has the largest warming in the winter and fall. The GFDL scenario has the largest warming of the three models, about 6.5°C annually, with the largest warming in the summer. All three scenarios have annual increases in precipitation. OSU has an increase of approximately 0.1 mm/day, with precipitation rising in all seasons. GISS has an increase of approximately 0.2 mm/day, with precipitation declining slightly in the fall. GFDL has an annual precipitation increase of only 0.05 mm/day, but rainfall drops by 5 mm/day in the summer. The large temperature increase and small rainfall increase combine to make GFDL the most severe scenario. This is especially true in summer months, when GFDL has the largest temperature rise of any scenario and virtually reduces rainfall to zero. OSU is the mildest scenario owing to the smaller

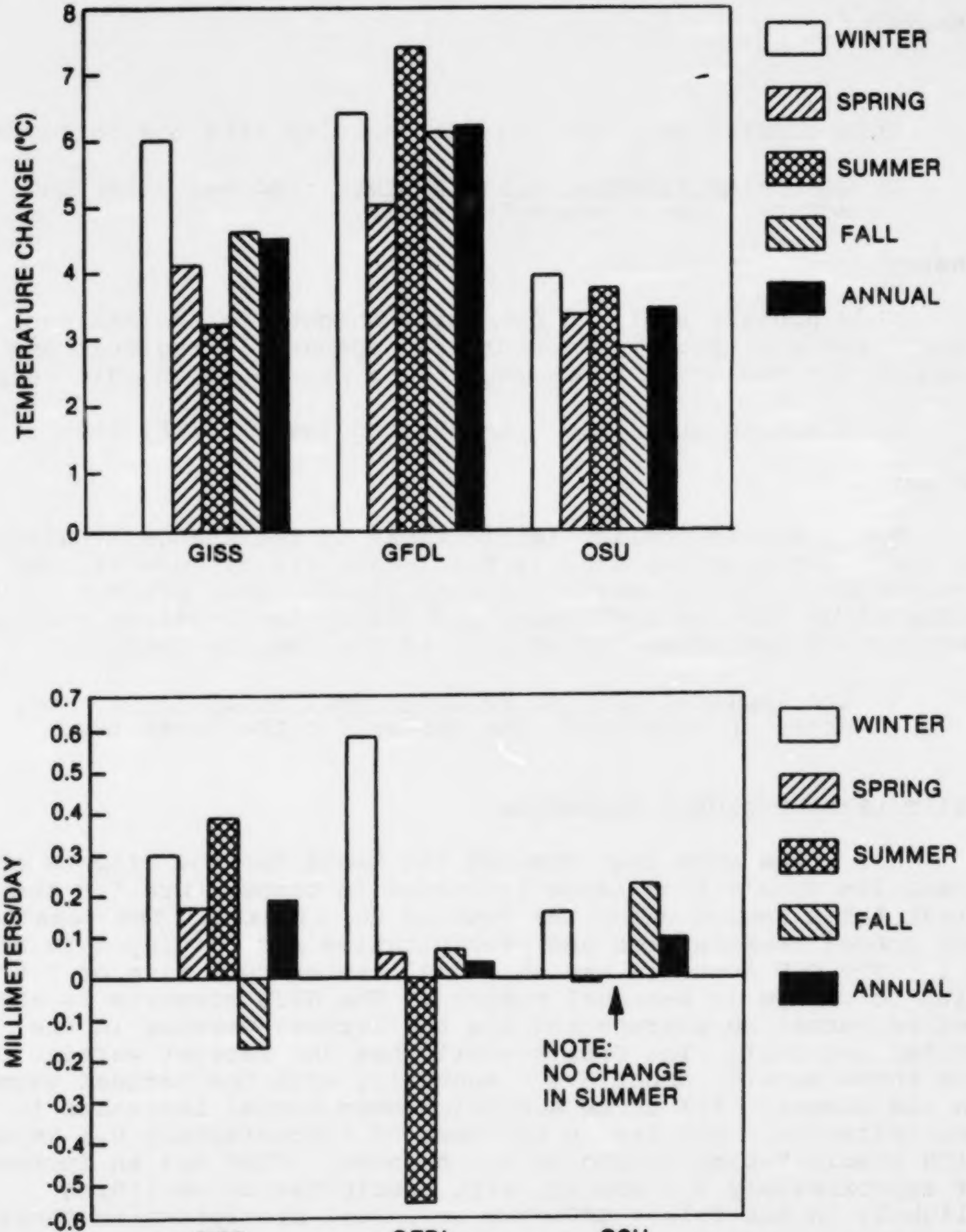

Figure 5-2. Average change in temperature (upper) precipitation (lower) over Great Lakes grid points.

temperature increase and GISS is in the middle in term of severity.

One limitation related to using the GCMs as a basis for climate change scenarios for the Great Lakes region is that the lakes are not well represented in the GCMs. The relatively large size of the GCM grid boxes results in little feedback from the lakes to the regional climate estimates from the GCMs.

RESULTS OF THE GREAT LAKES STUDIES

Lakes

Lake Levels

Geologic records indicate that Great Lakes levels have fluctuated as paleohistoric climates have been wetter and drier (Larson, 1985). Recent short-term variations have been the result of short-term changes in precipitation patterns. Croley and Hartmann examined the potential impacts of global warming on average lake levels.

Study Design

Croley and Hartmann used a water supply and lake level model of the Great Lakes Basin to estimate the potential impacts of climate change on levels of the Great Lakes (Croley, 1983a,b; Croley, 1988; Quinn, 1978). This model includes a separate model for each of the 121 watersheds in the basin. Croley and Hartmann simulated runoff in each of the sub-basins, overlake precipitation, and evaporation. Lake levels are very sensitive to evaporation; therefore, Croley and Hartmann ran each GCM scenario with different assumptions about evaporation.*
Finally,they used the current plans (Plan 1977 for Superior and Plan 1958-D for Ontario) and hydraulic routing models of outlet and connecting channel flow and estimated water levels on each of the Great Lakes.

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*In Volume _, Croley focuses on results from his latest run. This run includes assumptions that lead to relatively high amounts of evaporation and larger drops in lake levels. Earlier runs had less evaporation increases and less of a drop in lake levels. Results in this chapter include the latest run and an earlier run.

The regulation plan for Lake Superior failed under the GFDL scenario. To obtain an estimate of changes in levels for Superior-Huron, St. Clair, and Erie, Croley and Hartmann assumed that over a 30-year period, total inflows into Lake Superior (runoff + over-lake precipitation + diversions - evaporation) would equal total outflows, and Lake Superior levels would not change. Only 30-year average lake levels were calculated for the other lakes.

Limitations

The relationships in this model were developed for a cool and wet climate. The analysis did not account for changes in the consumptive uses of the lakes (due to population and economic growth or climate change), and it did not consider changes in the regulation plans, or increases or additions to diversions into or out of the lakes. The analysis also used the difference in vector winds from the GCMs as a proxy for the difference in scaler winds because GCM estimates of changes of scaler winds were not available. Thus, the wind estimates probably underestimate changes in windspeed (Rind, 1988). The uncertainty on winds is complicated by the uncertainties concerning evaporation. Different assumptions of evaporation affect the magnitude of lake level drop, but they do not affect the direction of change -- lake levels fall under all evaporation assumptions.

Results

Lake levels fall significantly under all three scenarios (see Table 5-2). The lake level changes are displayed in ranges from low to high evaporation.

Average levels for Lake Superior are about 0.4-0.5 m below average levels for the 1951-80 period under the OSU and GISS scenarios. No figure for Lake Superior is given for the GFDL scenario, since levels were held constant. These average levels are generally lower than extreme lows of recent history. Even though precipitation rises in all three scenarios, lake levels fall, primarily due to the higher temperatures. Apparently, only a large increase in rainfall or a large decrease in windspeeds can offset these changes. Lake levels are estimated to continue fluctuating on an annual basis. Specific estimates of fluctuation are not discussed here, since climate is assumed to remain constant.

Table 5-2. 2xCO$_2$ Scenarios: Reduction in Great Lakes Levels from 1951-80 Averages (meters)

Scenario	Superior	Michigan/Huron	Erie	Ontario
GISS	-0.43 to -0.47	-1.25 to -1.31	-0.95 to -1.16	NA
GFDL	NA	-2.48 to -2.52	-1.65 to -1.91	NA
OSU	-0.39 to -0.47	-0.86 to- 0.99	-0.63 to- 0.80	NA
	Transient Scenario (average rate of change per decade 1980-2060)			
GISS-A	-0.006	-0.055	-0.04	NA

NA = Not applicable.

Source: Croley and Hartmann, Volume __.

Croley and Hartmann also found that the flow in the St. Mary's increases by less than 1% in the GISS high rainfall scenario and drops by 13% in the drier OSU scenario for Lake Superior. The flow in the Niagara is estimated to be reduced by 2-30%. Croley and Hartmann did not estimate the flow of these rivers for the GFDL scenario.

The lowering of lake levels appears to be correlated with increased temperatures in the scenarios. All of the doubled CO$_2$ scenarios lead to declines in runoff to the lakes and increases in evaporation from the lakes. The reduction in runoff is largely the result of changes in snowpack accumulation and ablation. Snowpack in the Lake Superior basin is reduced by one- to two-thirds, and in the other basins, farther to the south, the snowpack is almost entirely absent. The reduction in runoff would reduce average streamflow in the basin. These results appear to be driven mainly by the temperature increase, since precipitation rises in all scenarios.

Evaporation increases under all model runs. The increase in evaporation varied under different assumptions about the relationship of evaporation to meteorology and ranged from 20 to 48%. For a given assumption about evaporation, higher temperature scenarios generally caused more evaporation. Lake level reductions could also be higher or lower, depending on these assumptions.

All of these changes cause a reduction in net basin supply (the sum of overlake precipitations and runoff minus evaporation) by 14-68%. The exception to this is the GISS scenario for Lake Superior. In that scenario, rainfall increases by 18%, leading to a 1% increase in net basin supply.

The Ontario regulation plan failed under all scenarios, including the transient run. Under these conditions, the system would not contain enough water to keep the level of Lake Ontario and the flow in the St. Lawrence River within ranges currently specified by the plan. The Lake Superior regulation plan failed under the GFDL scenario. Although net basin supply in Lake Superior increased under GISS, the regulation plan would require increased flow through the St. Mary's River to the water-short lower lakes, resulting in a net drop in Lake Superior levels.

These results are consistent with other studies done on lake levels and climate change. Both Cohen and Sanderson agree with Croley and Hartmann that lake levels would drop under various climate change scenarios. The other two studies, however, estimated lake levels would drop less than 1 m. Croley and Hartmann may have estimated greater changes because they used a more sophisticated runoff, evaporation, and routing model and because of different assumptions made about evaporation. Croley and Hartmann also used a more integrated approach and more variables from the GCMs. The estimates for GFDL may also be higher because the GFDL scenario used in this study had a higher temperature than the GFDL scenarios used by Cohen and Sanderson.

The results of the transient run (GISS A) are expressed as the average change in lake level per decade and are not indicative of what would happen in any particular decade. Lake Superior levels drop only 0.006 m per decade, while the other lake levels fall 0.04-0.055 m per decade. An extrapolation of the transient results to the decade of the 2060s (when the GISS A transient run reaches doubled CO_2 climate conditions) results in lake level reductions less than for the doubled CO_2 GISS scenario. This is because lake levels do not respond immediately to climate change, but must catch up. By the end of the transient scenario, the 2050s, lake levels fall by more than 0.05 m per decade.

Croley and Hartmann found that enough heat would reside in Lakes Superior, Michigan, Huron, and Ontario to maintain water surface temperatures at a sufficiently high level throughout the year, so that buoyancy-driven turnovers of the water column may not occur at all. This could significantly affect lakewater quality and aquatic life (see McCormick). Croley estimated that average surface water temperatures, which would be above 0°C, would significantly reduce ice concentrations.

Implications

Higher temperatures may lead to increased withdrawals of water from lakes for municipal consumption. If more powerplants are needed (see Energy Demand), the demand for cooling water will rise. Climate change may also result in more calls for diversion of water out of the basin for use elsewhere. However, lake levels may be lowered even more as a result of higher demand for withdrawals for use in the Basin owing to population and economic growth.

Hydropower production would be reduced, as flows through the St. Mary's, the Niagara, and the St. Lawrence Rivers would fall. Losses to hydropower were not estimated for the EPA study, although Linder's earlier work on hydropower losses by 2015 in New York State showed potential loss of 1600 to 2066 gigawatt hours (Linder, 1987). Presumably, hydropower losses would be higher under the doubled CO_2 scenarios. The impacts of lower lake levels on wetlands were not estimated, and the impacts on shipping and on shoreline infrastructure are discussed later in this chapter.

Lower lake levels and reduced river flow would likely adversely affect water quality in the Basin. Less water would allow for reduced dilution of pollutants. Forty-two hot spots occupy many bays and harbors along the Great Lakes. These are contaminated with a wide variety of halogenated organics and heavy metals, as well as remobilizable nutrients. Lower lakes may cause emergence and near emergence of these toxic sediments, through erosion, leaching, oxidization, or volatilization.

Effects of Lower Lake Levels

Coastal infrastructure around the Great Lakes has generally been built assuming average lake levels would not change. A drop in levels could make much of the current infrastructure unusable and necessitate reconstruction. Changnon examined the potential impacts and adjustments to infrastructure along the 101-km Illinois shoreline. This study and shipping analysis used the lower range of the lake level drops from Table 5-2 because subsequent analyses that gave different lake levels were performed too late to be incorporated.

Study Design

Changnon et al. interviewed experts about the possible impacts and costs of adjustment along the Illinois shoreline to the lower lake level estimates described above. Results are expressed in current dollars.

Limitations

This analysis did not use economic models and did use current prices. Results are based on expert judgment. Changnon et al. also assumed that lakes would reach the levels described above by 2030. Analysis of this assumption indicates that a doubled CO_2 climate may not be reached until the latter half of the next century. This study examined only the costs of rebuilding infrastructure and did not examine ecological impacts.

Results

The largest costs appear to accrue to recreational and commercial harbors (see Table 5-3). The major expenses are associated with dredging harbors and lowering bulkheads, which could cost approximately $200-400 million. If lake levels fall enough, keeping some harbors open (e.g., Waukegan, Illinois) may not be a cost-effective choice.

Changnon et al. concluded that slips and docks would be only slightly affected. Many of these probably would have been replaced anyway and could be set at lower levels as the lakes fall. (The impacts on commercial shipping in Lakes Superior and Erie are discussed in the shipping study.)

Intake valves for municipal and industrial consumption could be exposed and may have to be lowered or moved farther offshore. Outfalls for stormwater would have to be extended. Changnon et al. estimated that extending urban water intakes and stormwater outfalls could cost $16-17 million.

Although the exposure of more land could present some erosion problems, it could also enlarge many beaches. An additional 1-2.2 km^2 of beaches would be added to the Illinois shoreline. In all, Changnon et al. estimated that the costs of adjusting to lower levels of 1.25 to 2.5 m along the Illinois shoreline, excluding normal replacement of docks and piers, would be $220-430 million.

Table 5-3. Estimated Economic Impacts of Lowerings of the Levels of Lake Michigan Over a 50-Year Period (1990-2040).

Costs in millions of 1988 dollars to address future lake levels at indicated depths below average level of Lake Michigan (1951-1980).

		1.25 meters lower	2.5 meters lower
1.	Recreational Harbors		
	Dredging	30 to 50	75 to 100
	Sheeting	15	35
	Slips/Docks	20*	40*
2.	Commercial Harbors		
	Dredging	108	212
	Sheeting/Bulkheads	38	38
	Slips/Docks	40*	90*
3.	Water Supply Sources		
	Extending urban intakes	15	15
	Wilmette Harbor Intake	1	2
4.	Beaches		
	Facililty relocations	1-2	1-2
5.	Outfalls for Stormwater		
	Extensions and modifications	2	4
	TOTALS	$270 to $292 million*	$512 to 540 million

*Some costs could be partly covered by normal replacement expenditures over the 50-year period of changing level.

Source: Changnon et al., Volume __.

Ice Cover

Warmer winters would reduce ice cover on the Great Lakes. Some analysts have speculated that ice would be completely eliminated. Assel used a model to estimate the potential extent and duration of ice cover.

Study Design

Assel developed a statistical relationship between temperature and ice cover for this study. The models were developed for the three basins of Lake Erie, for the Lake Superior Western and Eastern Basins, and Whitefish Bay in Lake Superior. Whitefish Bay was included because it has the longest period of ice cover and acts as a choke point on shipping in and out of Lake Superior. Lakes Superior and Erie represent extremes in terms of air temperature regimes, lake depth, and heat storage capacity, and bound the range of potential ice cover changes.

Limitations

Assel's study did not consider the effects of wind and other variables on ice formation. Implicitly, the analysis assumed that winds stay the same. Stronger winds would make the ice season shorter than estimated, and weaker winds (and calmer waters) would make it longer. The model was built based on the relatively cool years of the 1960s and 1970s; therefore, the doubled CO_2 scenario temperatures are outside the range of winter temperatures in those years. However, the model simulated ice duration within 3 weeks of actual ice duration for the warm winter of 1982-83.

Results

Assel found that although average ice cover might be significantly reduced, ice would still form on the lakes (Table 5-4). The central basin of Lake Erie now averages 83 days of ice cover. Ice cover could be reduced to a total of 6-19 days and ice formations would generally be limited to near-shore and shallow areas. Whitefish Bay in Lake Superior currently averages about 115 days of ice cover. Under the doubled CO_2 scenarios, ice duration would be reduced to 69-80 days. Also, the maximum percentage of Whitefish Bay covered by ice would be reduced from close to 100% to 70-20%.

Table 5-4. Reduction in Ice Cover in Lakes Erie and Superior (average annual days of cover)

Lake	Base 1951-80	GISS Transient 2000s	 2030s	Doubled CO_2 GISS	 GFDL	 OSU
Erie West	93	83	51	26	23	35
Erie Cent	83	68	37	8	6	19
Erie East	97	79	46	6	5	13
Supr West	112	109	86	46	24	75
Supr East	108	105	83	43	19	69
Supr WFB	115	111	91	55	26	80

Supr = Superior; WFB = Whitefish Bay.

Source: Assel, Volume __.

The temperature rise does not appear to be warm enough to eliminate ice cover on the Great Lakes, but many winters could have no ice at all. The Lake Erie Central Basin is estimated to be ice-free from 11 to 22 years out of 30 years, rather than 1 out of 30 years, as estimated for base climate conditions. This result appears to be sensitive to depth, as estimates indicate that the deeper Lake Erie East Basin would be ice-free 60-84% of the time, and the shallow West Basin would be ice-free in 7-17% of the winters. Lake Superior would have ice cover in virtually all winters under the scenarios.

Assel found that ice cover reductions during the first 30 years of the transient scenario (model years 1981-2010) are not significantly different from reductions during the modeled current conditions. The length and extent of ice cover noticeably decline, beginning in the second 30 years of the transient scenario (2011-2040). By the last decade of the transient scenario, the 2050s, the extent of ice cover is almost identical to the GISS $2xCO_2$ coverage.

Croley also found that ice cover would be reduced. His analysis shows that average surface temperatures on all the lakes in the winter is above 0°C. Even if average temperatures are that high, water temperatures in near-shore and shallow areas, the areas to which Assel said ice would be limited, would be sufficiently cold to cause ice formation.

Implications

Ice cover reductions could have positive and negative effects. On the positive side, the shipping season would be extended (see below). Water would flow more freely through rivers and connecting channels allowing for more hydropower production in the winter. On the other hand, ice protects some aquatic life, such as whitefish, and protects shorelines against the erosive impact of high-energy waves (Meisner et al., 1987).

Shipping

With lower lake levels, ships would have to lower their cargo, or ports and channels would have to be dredged. However, the reduced ice cover would allow a longer shipping season. The additional days of transport may make up for the loss of capacity on each voyage.

Study Design

Keith et al. studied the potential impacts of changes in lake levels and ice cover on shipping in six ports: Two Harbors; Duluth/Superior and Whitefish Bays in Lake Superior; and Toledo, Cleveland, and Buffalo in Lake Erie. They used the "ECO Great Lakes Shipping Model," which includes current data on major ports and commercial ships in the Great Lakes, types of cargo, costs of transport, and operating costs. Keith et al. used lake level reductions from Croley and Hartmann to study the change in cargo capacity and costs per ton and they used the change in cargo capacity to estimate how many days of shipping would be needed to transport the same amount of cargo as transported at present. The latter figure was compared to ice duration reductions estimated by Assel to determine whether the shipping season was sufficiently extended to allow for transport of the same amount of annual cargo as currently transported.

Limitations

The analysis did not consider changes in the composition of the fleet or in the mix and amount of cargo. It also assumed that demand for shipping of goods did not change, even in response to availability of shipping. The analysis did not examine whether goods would shift to or from alternate means of transportation and how changes in the costs of shipping and in the shipping season would affect users. Keith et al. also assumed that channels were not dredged to be deeper. The analysis is useful for estimating the direction and approximate magnitude of change.

Results

The costs of shipping were estimated to increase due to lower lake levels. The effect on the cargo load for ships using the port of Buffalo are displayed in Figure 5-3. Under drops of 0.7-1.0 m in Lake Erie, which are the lake level reductions estimated by Croley for the OSU and GISS scenarios, cargo capacity would decrease by about 5-13%, and costs per ton would rise by the same amount. Croley's estimate from the GFDL scenario was that Lake Erie would fall 1.65 m (5.4 feet), but the shipping model does not include lake level drops of more than 5 feet. A drop of 5 feet would decrease cargo capacity per voyage by 27% and increase costs by 33%. Since lake levels in Lake Superior were not estimated to fall as much, the corresponding reduction in cargo capacity for ships on those ports would be in the range of 2 to 8%.

Sanderson estimated that lake level reduction of 0.2 to 0.6 m would increase Canadian shipping costs by 5%, assuming the current fleet and mix stayed the same. Although results are not directly comparable, since Keith et al. examined U.S. flag ships and ports, while Sanderson studied Canadian ships and ports, the estimates are of the same magnitude.

Whether the same amount of annual cargo can be transported depends mostly on how much lake levels drop. If the drop is sufficiently large, annual tonnage could be reduced. Figure 5-3 also displays the additional days needed to transport the same amount of cargo as is currently shipped through Buffalo. Under the approximate 2-3 foot drop of the wetter and relatively cooler OSU and GISS scenarios, another 15-40 days of shipping are needed. Assel estimated ice duration in eastern Lake Erie would be reduced by 84-91 days. Thus, under these scenarios, even with reduced capacity per voyage, there would be enough additional days of travel to transport even more goods. If lake levels fall 5 feet, which is less than estimated by GFDL, an additional 100 days of transport would be needed to handle the same amount of cargo. Ice duration in eastern Lake Erie is reduced by 92 days in this scenario, which would not allow enough time to transport the same amount of cargo, assuming the current fleet and demand for transport. The results appear to be more sensitive to changes in lake levels than reductions in ice cover.

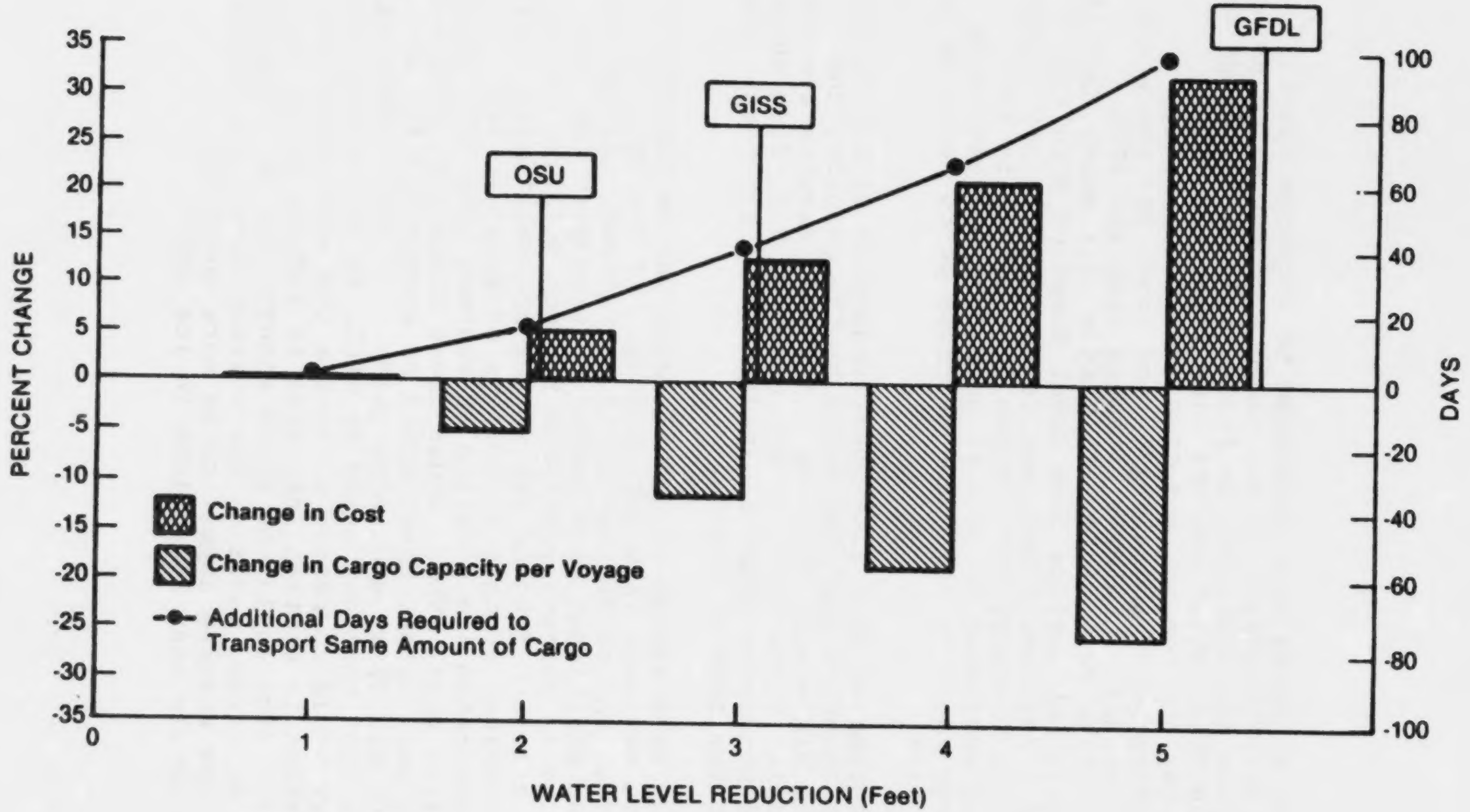


Figure 5-3. Impacts of lower lake levels and reduced ice cover on shipping, cargo capacity, costs, and days of transport for the Port of Buffalo.

Source: Keith et al., Volume __.

Keith and Willis used current dredging costs to estimate the cost of dredging the ports to restore current channel depths. The total costs of dredging the three ports in Lake Erie range from $26-82 million (1987 dollars).

Implications

Reduction in the tonnage per voyage or increased costs for dredging would raise shipping costs. However, with a longer shipping season, users of shipping such as powerplants would not have to carry large inventories to last through the winter and own enough land to store those inventories. Besides reducing costs, this could allow current lakefront storage areas to be used for other purposes. Whether these savings would offset higher shipping costs was not examined.

Dredging the ports and channels could degrade the water quality of the lakes. The sediments in many of these ports are toxic (which included many of the 42 hot spots), and disposal of the sediments could be complicated by their toxicity and by the reduced disposal areas resulting from lower lake levels.

Water Quality

Two studies estimated the temperatures and thermal structures of southern Lake Michigan and the Lake Erie Central Basin. The Lake Erie study estimates algal production and changes in dissolved oxygen levels. The Michigan and Erie analyses are used by Magnuson et al. to study changes in the thermal habitats of fish.

Thermal Structure of Southern Lake Michigan

Study Design

McCormick used a one-dimensional thermal structure model (Garwood, 1977) to estimate the heat content and structure of a site in south-central Lake Michigan. The model has been successfully applied to oceans and inland seas and was used by McCormick to analyze a site 150 m deep. GCM data for windspeed, temperature, humidity, solar radiation, and cloud cover were applied to hourly data from 1981 to 1984.

Limitations

McCormick used the years 1981-84 as his base case because hourly water temperature data are not available for 1951-80. Three years provide very limited baseline climate variability, although these years include cold and warm periods. Since the scenario may underestimate reductions in windspeed from the GCMs (see the discussion of the limitations of the lake level study), this analysis may overestimate wind-driven mixing in the upper layer and underestimate the length of time and degree of stratification. On the other hand, if the intensity of summer storm increases, then stratification may be weakened and shortened.

Results

McCormick estimated that the length of the stratified season would increase under all three scenarios. Figure 5-4 displays the mixed layer depth (the thermocline) over an average year. The higher heat content may cause the lake to begin thermally stratify, on average, about 2 months earlier than in the base case (in April as opposed to June). The stratified layers begin to deepen around late fall, as under current climate conditions.

Surface lake temperatures were estimated to be up to several degrees higher and warm more than lower levels. There appears to be a larger warming of the entire water column in the winter, about 2-3°C, than in the summer, which has a warming of about 2°C. The warmer lake temperatures are consistent with the studies of Croley and Assel, which suggest that midlake water will generally be ice-free. The earlier onset of stratification, reduced winds in the scenarios and greater temperature differences between lake layers could yield stronger density differences between upper and lower layers.

McCormick detected a significant decrease in the frequency of complete mixing of the lakes. The surface layer could be warmer and more buoyant, making it more difficult for entrainment and mixing to occur. Temperatures were too warm in the winters of some years to allow the lake to become isothermal, (the mixed layer would stay above the botton of the lake akk year) leading to a year-long stratification. This result is consistent with Croley's analysis.

Implications

Reduced turnover of the lakes could have serious implications for aquatic species in the lakes. Mixing of oxygen and nutrients would be disrupted, possibly affecting the abundance of life in the lower and upper layers of the lakes.

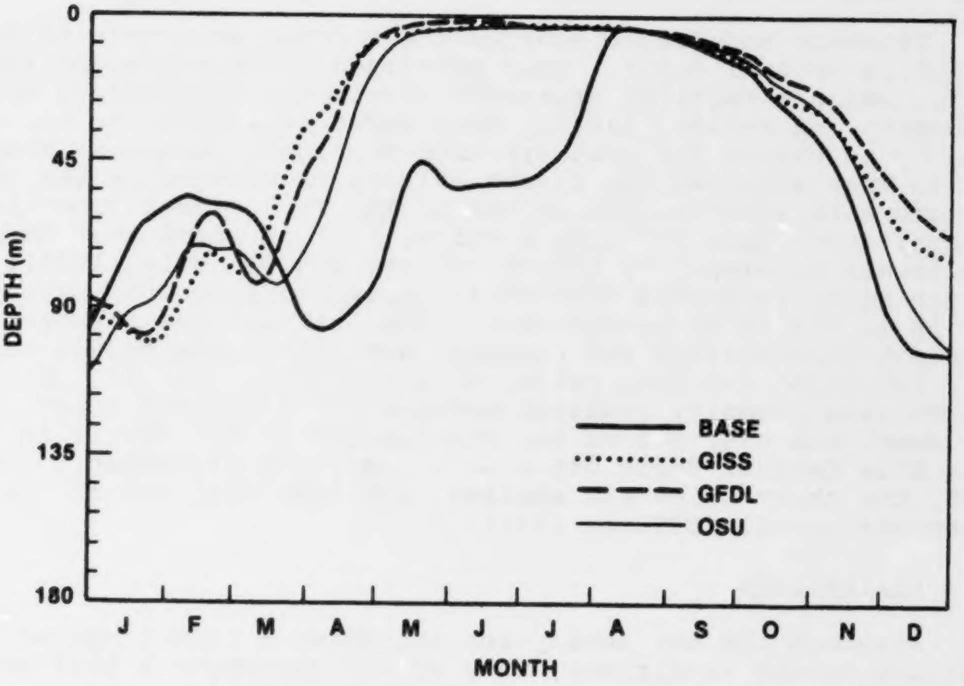


Figure 5-4. Lengthening of thermal stratification of southern Lake Michigan.

Source: McCormick, Volume __.

Eutrophication of the Lake Erie Central Basin

Nutrient loadings have made many areas of the shallow Lake Erie eutrophic at times. The shallow western and central basins of the lake are particularly vulnerable to eutrophication. Installation of pollution controls in recent years has improved water quality. Blumberg and DiToro analyzed whether climate change would have an effect on eutrophication in the Lake Erie Central Basin.

Study Design

Blumberg and DiToro modeled the thermal structure of the Lake Erie Central Basin. They developed a thermal model for the basin, using a modeling framework previously designed by Blumberg (Blumberg and Mellor, 1983). This model is similar to the one used by McCormick for southern Lake Michigan. Blumberg and DiToro then examined the direct effects of changes in the thermal structure on aquatic life in the basin. The outputs from the thermal model were fed into a eutrophication model that had been previously developed by DiToro (DiToro and Connolly, 1980). The latter model estimates what would happen to dissolved oxygen levels in the lakes by simulating the interactions between nutrient availability and plankton activity. The models were only run using two base years, 1970 and 1975. In 1970, the thermocline (density gradient between the upper and lower layers) was deep, and over 60% of the hypolimnion (lower level) in the Lake Erie Central Basin was anoxic (depleted of oxygen). In 1975, the thermocline was shallow, and less than 10% of the lower layer was anoxic (DiToro, 1987).

Limitations

Although the two base years encompass a wide range of baseline anoxic conditions, they do not represent a full range of climate variability. The analysis did not incorporate the actual reduction in nutrient loadings from the base years, or the estimated drop in lake levels from Croley's work. Lower lake levels would reduce the volume of the lower layer in Lake Erie, possibly increasing eutrophication. The models were not run for the winter, but Blumberg and DiToro tested the sensitivity of results to higher water column temperatures (due to warmer winter air temperatures) in the spring and found no significant difference in results. Blumberg and DiToro used the vector wind estimates from the GCMs, which may overestimate mixing in the upper layer.

Results

Blumberg and DiToro estimated that the Lake Erie Central Basin could remain stratified about 2 to 4 months longer than under current conditions, with the stratified season starting 2 to 6 weeks sooner and ending 2 to 7 weeks later. The temperature difference between the upper and lower layers of the basin are estimated to be greater under all scenarios, leading to less exchange of nutrients across the thermocline. The depth of the thermocline appears to be most sensitive to estimated changes in windspeeds. In two scenarios, GISS and GFDL, windspeeds are generally lower, and the thermocline is about 2 m higher than current depths. In the OSU scenario, windspeeds are estimated to increase and the thermocline becomes approximately 1 m deeper than current levels. A lowering of the thermocline depth by 2 m in the 25-m-deep Lake Erie Central Basin can reduce the volume of the lower layer by 20%, limiting total oxygen availability.

All three scenarios generally lead to decreases in dissolved oxygen levels compared to base case conditions despite differences in thermocline depth. The increase in area of the Lake Erie Central Basin that is estimated to become anoxic is shown in Figure 5-5. Dissolved oxygen levels increase only in the July 1970 case, and this occurs because the levels were near zero to begin with. Blumberg and DiToro concluded that the difference in oxygen content is caused by warmer lake temperatures, which raise bacterial activity enough to increase oxygen demand. The enhanced biological activity is combined with a more intense and longer stratified season to further lower dissolved oxygen levels. Lower thermocline depths, such as in the OSU scenario, result in even greater decreases in dissolved oxygen levels.

The estimated changes in the thermal structure of Lake Erie are comparable to McCormick's results for southern Lake Michigan. Both estimated that average temperatures in the water column would rise, that there would be greater differences in temperature between the epilimnion and hypolimnion, and that stratification would last longer. One major difference in the results is that stratification begins earlier and lasts longer in Lake Erie and begins earlier and breaks up at the same time as the present stratification in Lake Michigan. It is not clear whether this difference is attributable to different lake depths, surface meteorology used to force the models, or to surface boundary conditions in the calculations.

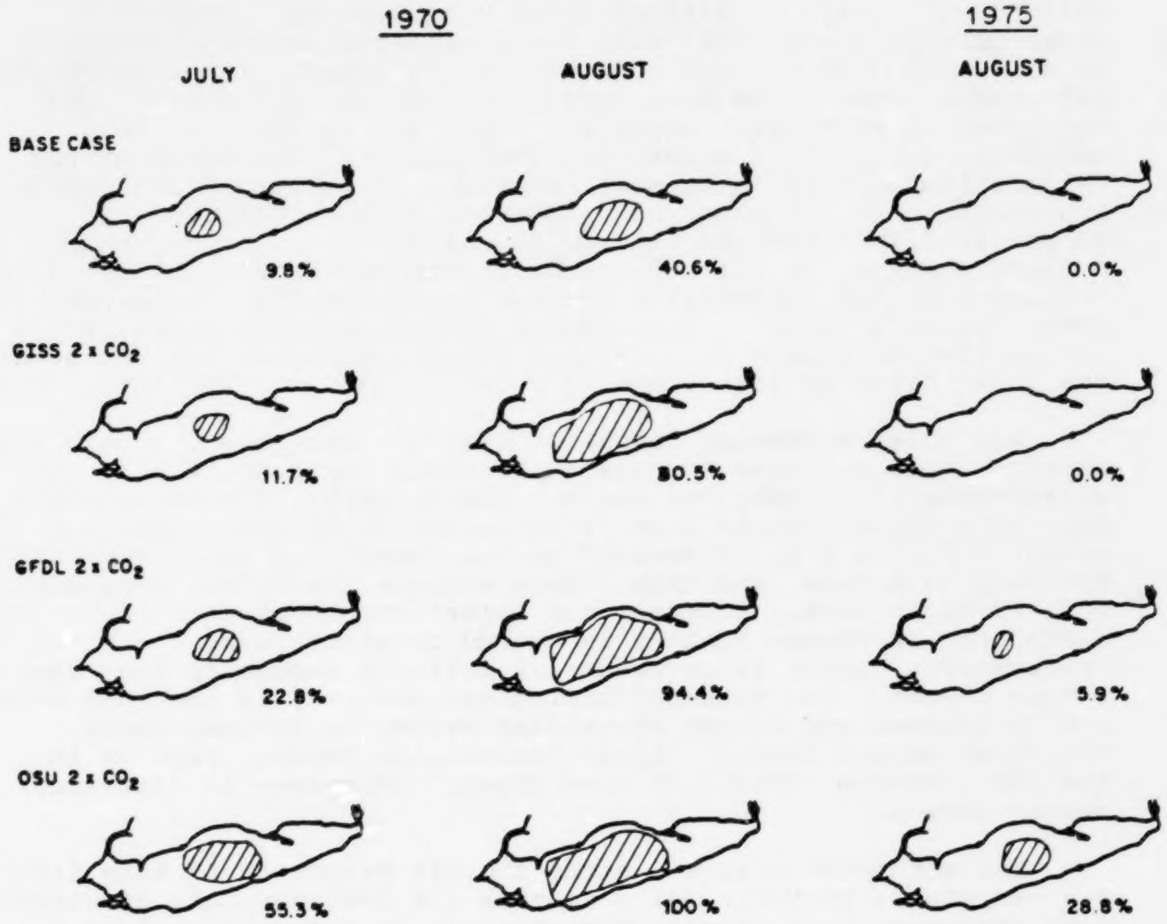

1970
1975
JULY
AUGUST
AUGUST
BASE CASE
9.8%
40.6%
0.0%
GISS 2 x CO_2
11.7%
80.5%
0.0%
GFDL 2 x CO_2
22.8%
94.4%
5.9%
OSU 2 x CO_2
55.3%
100%
28.8%

Figure 5-5. Area of central basin of Lake Erie that becomes anoxic.

Source: Blumberg and DiToro, Volume __.

Implications

Increased eutrophication could make the Lake Erie Central Basin uninhabitable for finfish and shellfish during the summer. This could reduce recreational uses of the lake such as swimming, fishing, and boating. It also could put more pressure on reducing sources of pollutants, especially such nutrients as phosphorous, from point and nonpoint sources.

Fisheries

The Blumberg and McCormick studies show that climate change would probably raise lake temperatures and reduce oxygen levels in certain areas. To get an initial sense of what these changes might mean for Great Lakes fish, Magnuson et al. examined the potential ecosystem, organism, and population responses to warmer temperatures.

Study Design

Magnuson et al. estimated changes in fish habitat, growth, prey consumption, and population for sites in Lakes Erie, Michigan, and Superior. The work used several approaches and models to examine the following:

- Changes in ecosystem activity, such as changes in phytoplankton populations, were estimated by using a community "Q_{10}" rule (Ruttner, 1931), which assumes that higher biological activity is associated with higher temperatures.

- Magnuson et al. used the Blumberg and McCormick thermal structure studies to estimate the potential effects on thermal habitats -- the niche in which temperatures are tolerable for species of fish. To estimate changes in habitats, the study used laboratory estimates of the temperature regimes preferred by fish (Magnuson et al. 1979; Crowder and Magnuson, 1983) and assumed that the lower layer of the Lake Erie Central Basin is uninhabitable. This study assumed that fish migrate to habitable sites when inshore temperatures are too warm. In addition, using a thermal model for streams (Delay and Seaders, 1966), the study calculated the change in habitat for brook trout in a southern Ontario river.

- Magnuson et al. used a food consumption and conversion model (Kitchell et al., 1977) to estimate the changes in growth and prey consumption at three near-shore sites in

Lakes Superior, Michigan, and Erie. This analysis assumed there were no limits on forage availability.

Limitations

The study did not consider changes in species interactions and prey availability. If prey is not sufficiently available, fish populations could decline. It did not examine the combined effects of reduced habitat and greater need for forage in the summer, which would combine to intensify species interactions. The analysis did not incorporate impacts resulting from lower lake levels, such as possible loss of wetlands, and it did not analyze the aquatic effects of the potential reduction in the frequency of lake turnover or the impacts of a reduction in ice cover. The introduction of new species, which could have negative impacts on existing fish, was not examined.

Any uncertainties associated with the McCormick and Blumberg studies would be carried over into the analysis on habitat. These changes in the lakes and littoral systems may have negative impacts on Great Lakes fish. These uncertainties could reverse the direction of results and lead to more declines in fish populations than indicated here.

Results

Phytoplankton production, zooplankton biomass, and maximum fishery yields are estimated to increase 1.25-3 fold with the biggest increase in phytoplankton production (2 to 3 fold) (Figure 5-6). The larger increases in biological activity are generally associated with larger temperature increases. The increase in phytoplankton provides more forage for zooplankton, which in turn, provides more forage for fish. The increase in phytoplankton can also enhance eutrophication, as was estimated by Blumberg and DiToro.

Magnuson and Regier found that the average annual thermal habitat for all fishes would increase. This was especially apparent for cold coldwater fishes such as lake trout, which could have more than a doubling of habitat (see Figure 5-7). The major reason for the increase in habitat is that more habitable waters would be found in the fall, winter, and spring. On the other hand, hotter temperatures in the summer could decrease habitats by 2-47%, depending on the temperature rise and species. The length of stream suitable for brook trout in the summer could be reduced by 25-33% due to higher temperatures.

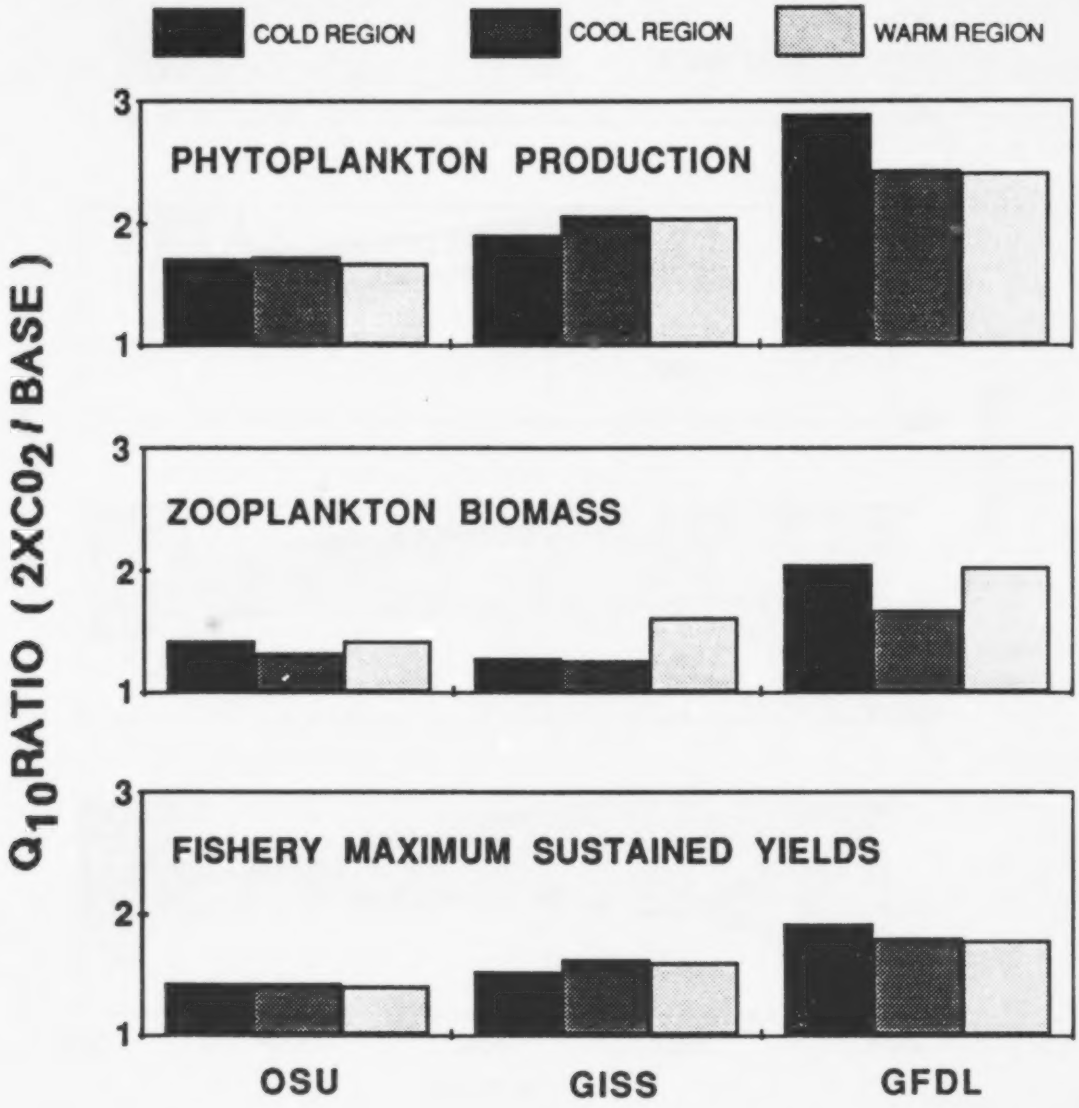


Figure 5-6. Increases in Great Lakes aquatic productivity.

Source: Magnuson et al., Volume __.

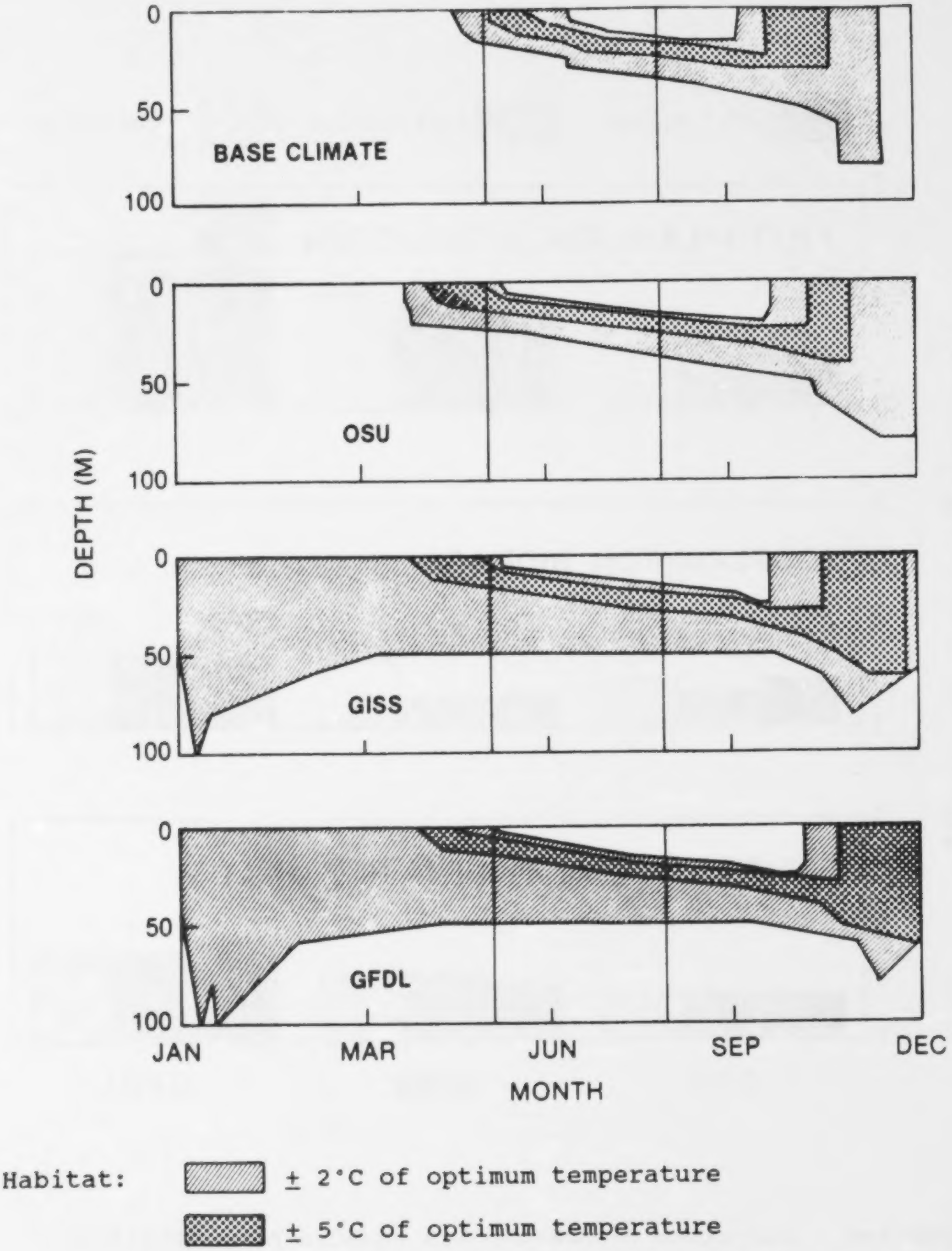


Figure 5-7. Increase in Great Lakes cold coldwater habitat

Source: Magnuson et al., Volume __.

Fishes are generally estimated to have increased body size under the scenarios. Cool and cold coldwater fishes could have 20-70% more growth, and warmwater fishes in warm areas could have 3.2 to 5.7 times greater growth. This assumes that prey availability increases. If prey availability does not increase, fish growth would also decrease owing to an inability to compensate for the increased metabolic costs of living in higher temperatures. Furthermore, the increased demand for forage may intensify species interactions and alter the food web structure.

The effects of reduced ice cover and possible reduction in wetlands on Great lakes fishes was not investigated, although Meisner et al. concluded that loss of wetlands due to lower lake levels could reduce spawning, nursery, and feeding grounds for fish in shallow areas, reducing fish populations (Meisner, et al., 1987).

Implications

If fish populations increase, there could be beneficial implications for commercial and recreational fishing. Presumably, commercial yields and sport fishing would increase, although certain species, such as brook trout in streams, may be reduced. A net increase in fisheries would lead to more employment in commercial fishing and tourism industries but, increase the need for maintaining water quality in the lakes. Increased demand on the forage base by predators and the introduction of new species could have negative effects, but these cannot be predicted and must be considered as surprises of unknown probability.

Forests

Climate change could affect the distribution and abundance of forests in the Great Lakes region. Overpeck and Bartlein examined the equilibrium range shift of forests, Botkin et al. studied transitional impacts on composition and abundance, and Zabinski and Davis analyzed the ability of trees to migrate along with a rapidly changing climate.

Potential Range Shifts

Study Design

Overpeck and Bartlein studied the potential shifts in ranges of forest types over eastern North America. This analysis suggests where trees are likely to grow in equilibrium 2xCO_2

climate conditions. It only indicates the approximate abundance of different species within a range, what the transitional effects of climate on forests might be, or how fast trees will be able to migrate to the new ranges. (See the Forestry chapter of this report for a discussion of the study's methodology and limitations.)

Results

Under all three $2xCO_2$ scenarios, the range of spruce, a major component of the boreal forests, would shift almost entirely out of the region entirely. Northern hardwoods, such as birch and northern pine species, would shift to the north, but would still be in the region. Oak trees, which are mostly found in the southern part of the region, would be found all over the region in the warmer conditions. The abundance of prairie forbs (shrubs) would increase in the region and southern pines could migrate to the southern part of the region.

Transitional Effects

In contrast to Overpeck and Bartlein, Botkin et al. examined the transitional effect of climate change on forests and equilibrium conditions.

Study Design

Botkin et al. used a model of forest species growth and competition to estimate the effects of climate change on Great Lakes forests (Botkin et al., 1972, 1973). This model, which is known as a stand simulation model, can be used to estimate the transitional changes in composition and abundance of forests species in response to environmental changes such as higher temperature and precipitation.

Botkin et al. studied two diverse sites in the Great Lakes region. The first is in Mt. Pleasant, Michigan, a heavily settled area dominated by northern hardwoods and oaks, where commercial forests are an important resource. The other site is in Virginia, Minnesota, an undeveloped area dominated by boreal forests that have commercial and recreational uses.

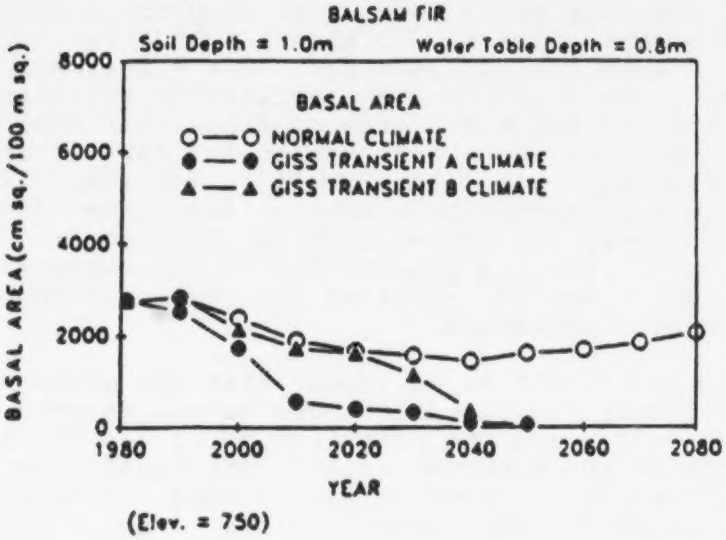
Limitations

The model includes all dominant tree species in the northern United States and assumes that seeds from all these trees are universally available throughout the region. Species with predominantly southern distributions are not included; therefore, the model does not estimate whether they could grow in the region under the warmer climate. (Overpeck found that southern pines may migrate into the southern part of the region.) Thus, the stand simulation model does not accurately estimate migration of trees, either within the region or from other areas. In addition, the model does not account for fertilization effects of CO_2, although CO_2 may not have positive effects in the competitive environment of unmanaged ecosystems (see Botkin). Botkin's analysis did not account for introduction of new pests into the region for the possibility of increased frequency of fires, or the combined impact of changes in tropospheric gas levels and UV-B radiation.

Results. Botkin et al. found that the abundance of species could significantly change in three to six decades. Figure 5-8 displays results from the transient scenarios for balsam fir and sugar maple at the Minnesota site. The basal area of balsam fir starts to decline in three to six decades. Potential declines in several decades are also seen in simulations of white cedar and white birch in the Minnesota site. Sugar maple, which has negligible basal area in the current climate, starts to exhibit significant growth within three decades in both transient scenarios.

Botkin et al. estimated the doubled CO climate would cause major changes in forest composition throughout the region. Results from the Mt. Pleasant site indicate that tree biomass at dry sites, which now have oak and sugar maple, could be reduced by 73 to 99% and converted to oak savannas or even prairies. Relatively wet soil sites might be converted from sugar maple to mostly oak woodlands with some red maple. Biomass at these sites could be reduced by 37 to 77%.

In the Minnesota site, the boreal forests could be replaced by northern hardwood forests, now characteristic of areas to the south (see Figure 5-9). Relatively dry areas, such as the Boundary Waters Canoe Area where balsam fir dominates, and upland areas where white birch and quaking aspen dominate, could be replaced by forests consisting mainly of sugar maples. Where currently saturated soils in these upland areas become drier and better sites for tree growth, wood production may increase. However, bogs that now contain white cedar could become treeless. This is because no species which could tolerate warmer bog conditions are currently in the region. More southerly species could be transplanted.



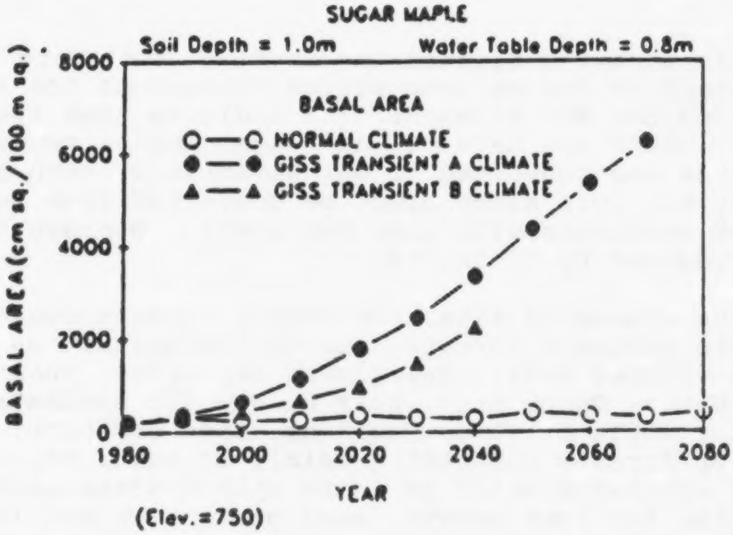
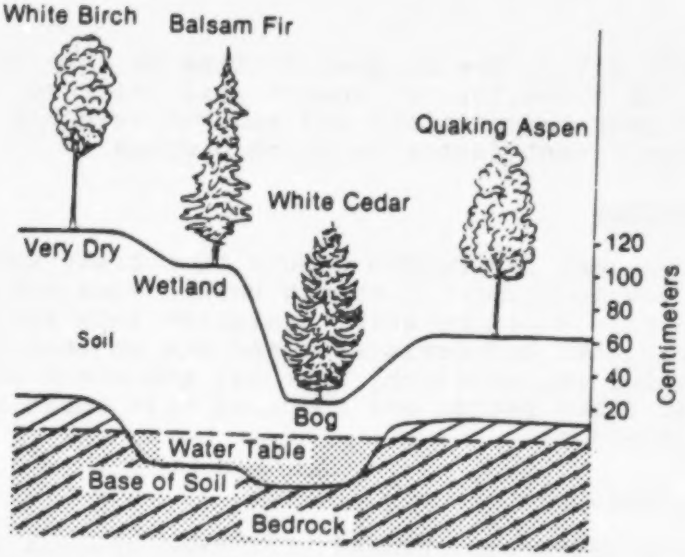


Figure 5-8. Change in forest composition during the next century for a deep, wet, sandy soil in the Boundary Waters canoe area.

Source: Botkin et al., Volume __.

NORTHERN MINNESOTA NOW


White Birch
Balsam Fir
Quaking Aspen
White Cedar
Very Dry
Wetland
Soil
Bog
Water Table
Base of Soil
Bedrock
120
100
80
60
40
20
Centimeters

NORTHERN MINNESOTA UNDER 2XCO$_2$ CLIMATE

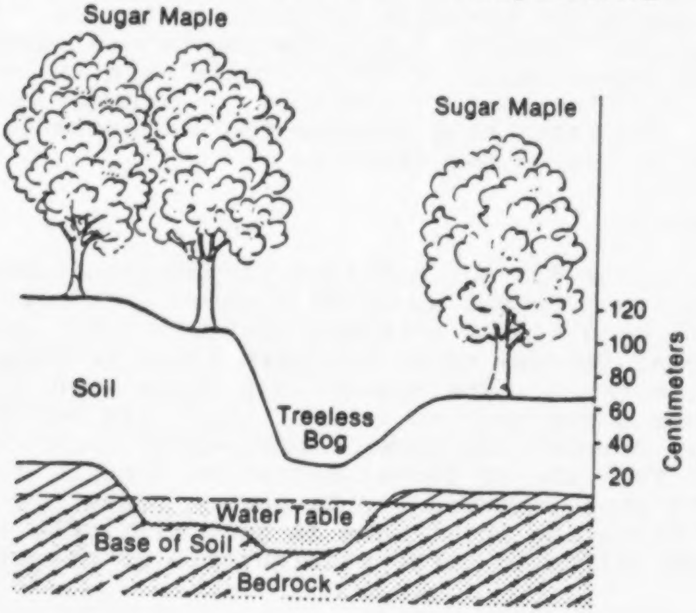

Sugar Maple
Sugar Maple
Soil
Treeless Bog
Water Table
Base of Soil
Bedrock
120
100
80
60
40
20
Centimeters

Figure 5-9. Effects on northern Minnesota forests (Virginia, Minnesota).

Source: Botkin et al., Volume __.

In both sites, the biggest decline is seen in the hotter and drier GFDL scenario. Decreased soil moisture, which is a result of higher temperatures and reduced rainfall, appears to be the most significant factor reducing biomass.

Forest Migration

Both Overpeck and Botkin assume that trees would be able to migrate to new locations (although Botkin does not assume southern species would be able to migrate into the Great Lakes region). Zabinski and Davis examined the potential range shifts of sugar maple, yellow birch, hemlock, and beech currently found in the Great Lakes region and compared that shift with potential rates of migration.

Study Design

Zabinski and Davis assumed that tree species only grow in climate with temperatures and precipitation identical to their current range. They determined the location of potential species ranges under the GISS and GFDL scenarios. The climate values were determined by extrapolating between gridpoints. Zabinski and Davis examined the potential migration of the species by assuming that the doubled CO_2 climate would not occur until 2090, and that these species could migrate into new regions at the rate of 100 km per century.

Limitations

The analysis did not consider competition among species or whether migratory routes would be blocked. It also did not analyze soil conditions, nutrient availiability, sunlight, and other relevant factors about northern areas to determine if trees would survive there. The assumptions about when doubled CO_2 climate would occur and the rate of migration are both optimistic. Doubled CO_2 climate conditions could occur sooner than 1990. The rate of forest migration used is double the maximum rate ever recorded for temperate trees. A faster warming and slower migration would make it more difficult for forests to keep up with shifts in range attributable to climate change.

Results

Under the wetter GISS scenario, the potential ranges of sugar maple, yellow birch, hemlock, and beech move markedly northward to central Canada. The results for hemlock and sugar maple are displayed in Figure 5-10. The stippled area shows the potential range, and the black area shows how far the trees could

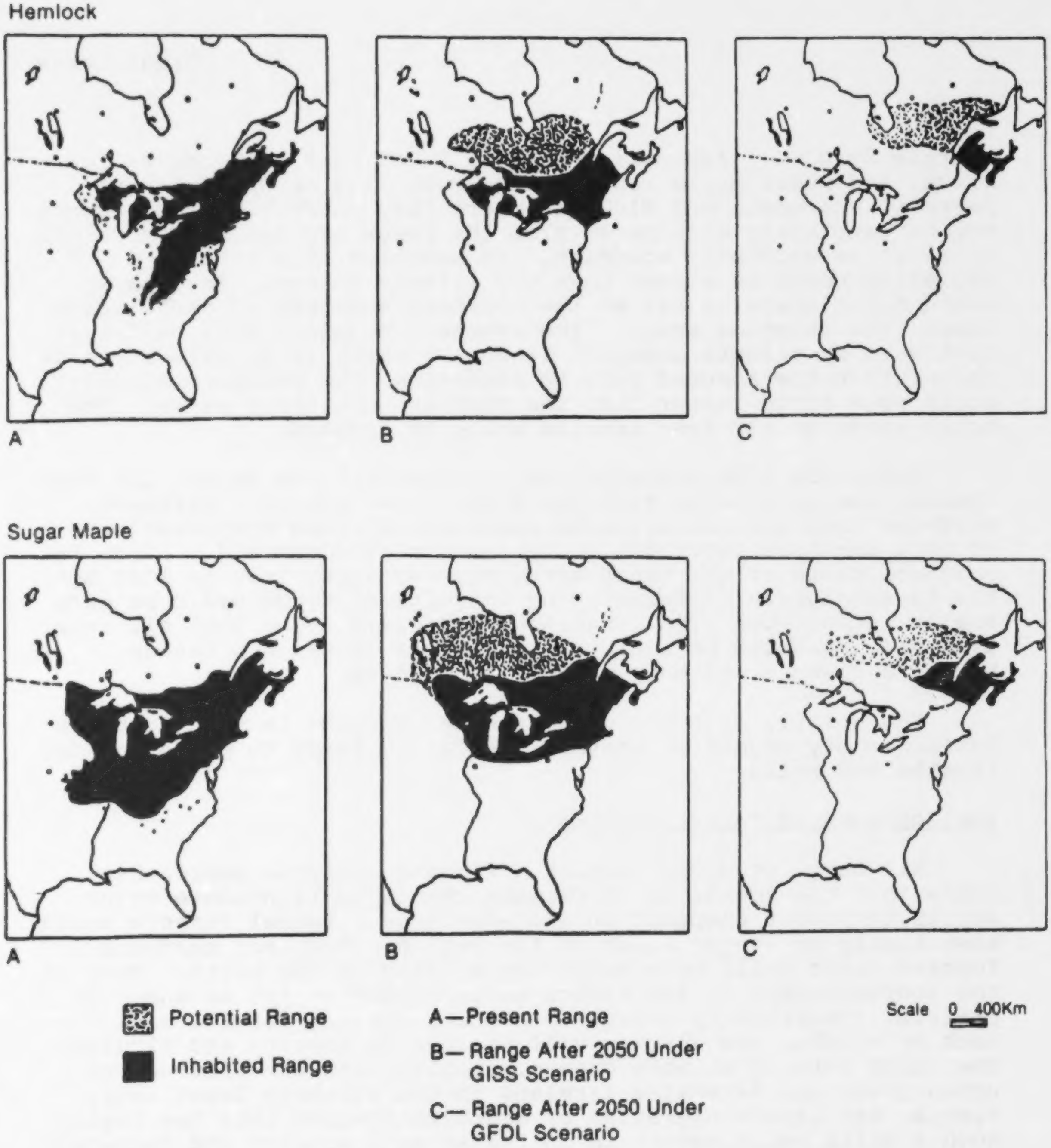

Hemlock
A
B
C
Sugar Maple
A
B
C
Potential Range
Inhabited Range
A—Present Range
B—Range After 2050 Under GISS Scenario
C—Range After 2050 Under GFDL Scenario
Scale 0 400Km

Figure 5-10. Shifts in range of hemlock and sugar maple.

Source: Zabinski and Davis, Volume __.

migrate by 2090. Zabinski and Davis found that hemlock, yellow birch, and sugar maple could become much less abundant in the parts of Wisconsin and Michigan where they currently grow. Beech may be completely eliminated from the lower peninsula of Michigan where it is presently abundant. In addition, the rate of migration would be slower than the climate change. The trees would not migrate as far as the northern boundary of the climate range (the stippled area). The southern boundary will be driven northward by climate change. Since the shift in climate zones is faster than the assured rate of migration, the southern boundary would move north faster than the northern migration rates. The total range of all four species would be reduced.

Under the GFDL scenario, which is hotter and drier, all four species are eliminated from the Great Lakes region. Northern hardwood tree species might be replaced by trees characteristic of more southern latitudes or by prairie or scrubland. Since the southern range of the trees moves farther north than in GISS but the trees migrate no faster, the inhabitated range would be much smaller than under GISS. Zabinski and Davis found that all four tree species would be confined to an area in eastern Canada having a diameter of only several hundred km.

The ability of the four species to survive in more northern latitudes may depend on whether they could adapt to different day lengths and soils.

Implications of Forest Studies

All three studies, through different analytic approaches, agree that the scenarios of climate change would produce major shifts in forest composition and abundance. Boreal forests would most likely no longer exist in the region. Northern hardwood forests might still be present, especially in the north. Much of the southern part of the region could become an oak savannah or prairie. Uncertainty exists concerning whether forests will die back or whether new species will be able to migrate and flourish. The rapid rate of climate change, coupled with the presence of urban areas and extensive farmland in the southern Great Lakes States, may impede migration of southern species into the region. Such a shift could result in increased soil erosion and decreased water quality. In addition, higher tree mortality and drier soils could increase fire frequency. Increased environmental stress might increase pathogen-related mortality in plants. Shifts in forest composition and abundance may have implications for wildlife in the region.

This shift in species also could have significant impacts on the commercial forest industry in the region. The industry currently harvests softwoods for production of pulp, paper, and construction materials. These species would decline and be replaced by oaks and maples, which are useful for furniture but take longer to become fully grown. Red maple, which may be more abundant in the southern area, is not currently used commercially. Changes in forest abundance may also affect tourism.

Agriculture

The agriculture studies combine analyses of impacts on the region and across the country. Ritchie et al. studied the potential impacts of climate change on crop yields in the region. Adams et al. then used the results from this study and other regional crop yield analyses to estimate economic adjustments by farmers. Easterling studied how a typical Illinois corn farmer would try to adapt to climate change.

Crop Yields

Study Design

Ritchie et al. used crop growth models to estimate the impacts of climate change on yields for corn and soybeans in the Great Lakes States (Jones and Kiniry, 1986). The two physiological models examine the direct effects of temperature and precipitation on crop yields. Ritchie et al. also used simple estimates of increased photosynthesis and decreased transpiration to conduct a sensitivity analysis of the combined impacts of change in weather and CO_2 fertilization on crop yields. In addition, he studied whether crops currently in southern areas may mitigate climate effects.

Limitations

The analysis of combined effects is new research and will need further development and refinement. The model runs use simple parameters for CO_2 effects, assume higher atmospheric concentrations of CO_2 than are predicted, and may be overestimates of crop yields. (See the Agriculture chapter of this report.)

All the scenarios assumed that soils were relatively favorable for crops, by having low salinity and no compaction, and they assumed no limits on the supply of all nutrients. In addition, the analysis assumed farmers would make no technological adjustments to improve crop yields. Possible negative impacts due to changes in storm frequency, droughts, and pests and pathogens were not factored into this study. The percentage changes for Duluth are very large because current yields are very low relative to other sites.

Results

Ritchie et al. found that temperature increases alone could reduce crop yields everywhere in the region except the northernmost latitudes, such as Duluth, where yields could increase depending on rainfall availability. Corn yields could decrease from 3 to 60% depending on climate and water regime (dryland or irrigated). However, Duluth, the most northern site, could see increases of 49-86%. Current dryland and irrigated corn yields are lower in Duluth than in the more southern sites. Dryland yields in Duluth under climate change would be equal to other sites, and irrigated yields would exceed the other locations.

Dryland soybean yields are estimated to drop by 3-65% in the region, except in the north. There, dryland yields decrease by 6% under GFDL, but increase by 109% under the wetter GISS. Under irrigated scenarios, soybean yields in the north increase by 96 to 153%. Even with the increase in output, the soybean yields in Duluth are still lower than in areas to the south.

Table 5-5. Effects of Climate Change Alone on Corn and Soybean Yields in Great Lakes States (ranges are GISS-GFDL and are % change from base)

	Corn		Soybeans	
Site	Dryland	Irrigated	Dryland	Irrigated
Duluth, MN	+49 to -30	+86 to +36	+109 to -6	+153 to +96
Green Bay, WI	-7 to -60	-3 to -44	-3 to -65	+3 to -26
Flint, MI	-17 to -48	-14 to -38	-6 to -51	+6 to -11
Buffalo, NY	-26 to -47	-18 to -38	-21 to -53	+6 to -6
Fort Wayne, IN	-11 to -51	-15 to -48	-2 to -58	0 to -19
Cleveland, OH	-26 to -50	-19 to -43	-16 to -59	-1 to -14
Pittsburgh, PA	-22 to -55	-19 to -45	-13 to -59	0 to -13

Source: Ritchie et al., Volume __.

The reduction in yields in the south is due mainly to the shorter growing period resulting from extreme summer heat. Production in the north is currently limited by the long winter, so a longer frost-free season results in increased yields.

Ritchie found that the demand for irrigation would rise between 20 and 173% under the GFDL scenario and up to 82% under GISS, although some sites under GISS were estimated to have up to 21% reductions in demand of up to 21%.

The combined effects of higher concentrations of CO_2 and climate change could increase yields if sufficient rainfall is available. If it is not, yields could rise or fall. Dryland corn and soybean yields rise up to 135% under the GISS scenario and up to 390% in Duluth. In the GFDL scenario, however, yields fall up to 30% or rise 17%, again, except for Duluth, which has an increase of 66-163%. Irrigated yields for corn rise and fall under both scenarios, but irrigated soybean yields rise 43-72% in the south and up to 465% in Duluth. The combined effects lead to an estimated reduction in demand for irrigation for corn of 26 to 100% under both scenarios, whereas irrigation needs for soybeans under GFDL rise by 65-207% and range in GISS from a reduction of 10% to an increase of 32%.

Ritchie found that use of a longer season corn variety could reduce the negative effects of climate alone, under the GFDL scenario, but still result in net losses.

It is not clear whether crop yields would rise or fall in the region. Among other factors, this will depend upon how CO_2 and climate change combine to affect crop growth and on how hot and dry the climate becomes. Yields and the potential demand for irrigation appear to be quite sensitive to rainfall, being higher under relatively drier scenarios. If climate change is severe enough, as under the GFDL scenario, yields could fall. In general, irrigation demand would rise, but some significant exceptions exist.

Implications. The potential shifts of agriculture northward are discussed below. Since the demand for irrigation is generally higher, it could become a more attractive option for farmers in the region. Whether more irrigation is actually used will depend on its costs and changes in revenue results.

Regional Shifts

Ritchie et al.'s analysis only estimates changes in potential yields for the Great Lakes region. How much farmers actually grow will depend in part on what happens elsewhere. If the relative productivity of agriculture rises, farmers will probably increase acreage. If productivity falls, they would most likely cut back. Adams et al. examined how different regions of the United States may react to potential productivity changes. Results are presented here for the Great Lakes region only.

Adams et al. modeled potential nationwide shifts in crops using the Great Lakes analysis and analyses of shifts in other regional crop yields. He did the analysis for yields attributable to climate change alone, and for the combined effects of climate and enhanced CO_2 concentrations. Adams et al's analysis did not account for the effects of climate on agriculture in other countries. How U.S. and regional agriculture respond to climate change may be strongly influenced by changes in relative global productivity and demand. (See the Agriculture chapter of this report for a discussion of the study's design and limitations.)

Results. Adams et al. estimates of acreage changes for the Great Lakes States are shown in Table 5-6. It appears that land devoted to agriculture in the Great Lakes region would not change significantly in response to climate change. The results indicate a slight tendency to increase acreage in the northern Great Lakes States, although only by small amounts. Land use in the Corn Belt would most likely be unchanged.

The relative increase in acreage in the north is consistent with Ritchie et al.'s results. Despite the yield reductions estimated by Ritchie et al. for the southern Great Lakes States, acreage would not be significantly reduced.

Table 5-6. Percentage Change in Acreage for Great Lakes States of Iowa and Missouri

	Climate Change Alone		Climate and CO_2	
Area	GISS (%)	GFDL (%)	GISS (%)	GFDL (%)
Lake States	+3	0	%1	+10
Corn Belt	+2	-6	-1	-6

Implications

The results of Adams et al. and Ritchie et al. suggest that northern regions will become more attractive for agriculture, although more extensive analysis is needed to confirm this result. The presence of thin, glaciated soils may limit this shift. If it occurs, such a shift could have significant implications for development of the north. Additional acreage could be converted from current uses, such as forests, to agriculture. Increased erosion and runoff from this additional acreage would pollute groundwater and streams and lakes in relatively pristine areas. Enhanced agriculture may increase the need for more shipping as lower lake levels raise shipping costs.

Adjustments by Illinois Corn Producers

Farmers may make many adjustments to climate change such as planting different crop varieties, planting earlier in the season, irrigating, and using different fertilizers. Easterling examined how a typical corn farmer in Illinois would react to climate change.

Study Design

Easterling presented several professional crop consultants with the GISS and GFDL climate change scenarios and with estimates of corn yields and prices for climate effects alone from the Ritchie et al. and Adams et al. studies. Based on the interviews, a set of decision rules were established to estimate how a typical Illinois corn farmer would alter farming practices in response to the climate and agriculture scenarios.

Limitations

The climate change scenarios involve climate conditions not experienced by the experts. Their estimates of how farmers would respond are not based on experience with similar conditions but on speculation. The results of the combined climate and CO_2 sensitivity analyses were not presented to the experts. The analysis is specifically for Illinois corn farmers and cannot be extrapolated to other areas or crops.

Results

Easterling found that the degree of adjustment depends on how much climate changes. Under the wetter GISS scenario, farmers could make adjustments to help mitigate the impacts of higher temperatures. Such adjustments could include planting earlier in the spring to avoid low soil moisture levels in the summer, using full-season corn varieties for earlier planting, and changing tillage practices and lowering planting densities to better conserve soil moisture. Under the hotter and drier GFDL scenario, corn production might not be feasible. Farmers would likely install irrigation systems; switch to short-season corn, soybeans, and grain sorghum; and perhaps remove marginal lands from production. This last conclusion is consistent with the Adams et al. study.

Implications

Although farmers have a variety of adjustment options to help cope with climate change, they may have great difficulty coping with extreme changes such as the dry climate implied by the GFDL scenario. Use of more irrigation would have negative implications for water quality, although this would be partly counterbalanced by any retirement of marginal lands.

Electricity Demand

Study Design

Linder and Inglis estimated the national changes in demand for electricity for the years 2010 and 2055. They first estimated the change in electricity demand due to gross national product (GNP) and population growth, and then factored in demand changes based on change in climate. The results for the Great Lakes States are displayed here. The Great Lakes analysis did not consider any reductions in hydropower production resulting from drops in lake levels. (See the Energy chapter of this report for a description of the study's design and limitations.)

Results

Estimates of changes in annual demand induced by climate change are displayed in Table 5-7. The results for 2010 are a range based on GISS transient scenarios A and B, and the results for 2055 are just for GISS A. A latitudinal difference exists within the Great Lakes region. In the northern States of Minnesota, Wisconsin, Michigan, northern Ohio, and upstate New York, annual demand falls. The reduced demand for winter heating is apparently greater than the increased demand for summer cooling. This is true in 2010 and 2055 when scenario temperatures are, respectively, 1 and 4° higher than the base case. Annual demand in the southern part of the region (in Illinois, Indiana, southern Ohio, and Pennsylvania) rises because increased cooling needs are apparently greater than reductions in heating.

Although annual demand could fall in some areas, new generation capacity requirements for all utilities in the region would be higher now because of increased summer cooling needs. New generation capacity requirements needs are estimated to rise by 3 to 8% in 2010 and by 8 to 11% in 2055. Whether costs would rise in the next two decades is not clear. Linder estimated that under the gradual warming of GISS B, cumulative capital costs in the region would be reduced by $1.3 billion, while under the more rapid warming of GISS A, costs would increase by $300 million. By 2055, costs would rise to $23 to 35 billion under GISS A. However, the cost to build additional capacity to meet GNP and population growth without climate change would be $488 to 715 billion.

Table 5-7. Estimated Change in Electricity Demand Induced by Climate Change for Great Lakes Utilities (%)

Utility	Annual (2010)	Annual (2055)
Minnesota	-0.2 to -0.3	-1.2
Wisconsin	0.4 to -0.5	-2.3
Michigan	-0.2 to -0.3	-1.2
Upstate New York	-0.2 to -0.5	-1.3
Ohio, north	-0.2 to -0.3	-1.3
Ohio, south	0.4 to -0.5	2.1
Pennsylvania	0.4 to -0.5	2.2
Illinois	0.5	2.0
Indiana	0.4	1.9
Total	Negligible	<1

Source: Linder and Inglis, Volume __.

Implications

Increased capacity requirements could place additional stress on the region. Powerplants may need cooling water and may seek to obtain it from rivers or the Great Lakes. Fossil fuel plants could add more pollutants to the air. The lake level analysis indicates that hydropower production from the lakes would be reduced, further increasing the demand for energy from other sources.

POLICY IMPLICATIONS

Climate change could raise many issues for policymakers in the region to address. Fundamentally, decisionmakers may have to cope with water use, water quality, and land management issues. They will probably have to respond to a decline in water availability, increased demand for water, poorer water quality, and shifts in land use, including the possibility of expanded agriculture in the north.

Most likely, many of the decisions in response to climate change, especially issues concerning water management, necessarily will be made on an international basis. Both Canada and the United States oversee the regulation of the lakes, water quality, and diversions of water out of the basin.

Water Supply Issues

Lake Regulation

One important issue to be faced by both countries may be regulation of the lakes. Lower lake levels may require altering plans for Lakes Superior and Ontario. This would involve tradeoffs among the needs of shippers, hydropower, shoreline property owners, and infrastructure, and downstream needs, in deciding how high to keep the lakes and rivers. For example, maintaining high water levels in the lakes to support shipping, hydropower, consumption, and improved water quality would be at the expense of shipping, hydropower, consumption, and water quality in the St. Lawrence River. Additional structures to control the flow on the lakes may be an option. The International Joint Commission should begin to consider the potential impacts of climate change on lake regulations in its long term planning.

Withdrawals

Even without climate change, population growth would increase demand for water for municipal and industrial consumption and power generation. Climate change would most likely intensify the demand for withdrawals from the lakes for even more uses within and outside the basin. Municipal consumption would rise (Cohen, 1987), additional powerplants may use water from the lakes for cooling purposes, and farmers in the region may need more water for irrigation.

Others outside the Great Lakes may demand diversion of water from the basin. The 1986 Water Resources Development Act prohibit such diversion without the agreement of all Great Lakes governors and prohibits the Federal Government from studying this issue. Increased diversion through the Chicago Ship Canal was requested this summer to raise water levels on the drought-starved Mississippi River. The U.S. Army Corps of Engineers rejected the request.

Shipping

Any response to the potential impacts on the shipping industry may be costly. Possibilities include dredging of both ports and connecting channels. Dredging could cost tens, if not hundreds, of millions of dollars. In addition to the high capital costs of dredging, substantial environmental costs could be incurred in disposing of dredge spoils contaminated with toxic chemicals. If dredging were not undertaken, cargo loads would be lower and would possibly impair Great Lakes commerce.

Pollution Control

Climate change will probably lead to stricter pollution control to maintain water quality. Reduced riverflow, lower lake levels, changed thermal structure, and potentially reduced groundwater supplies may necessitate stricter standards and additional controls on sources of pollution. A need may exist for better management of nutrient runoff from farms into shallow areas, such as the Lake Erie Western and Central Basins. Many pollution control institutions, such as EPA and State and local water quality agencies, would have the authority to impose appropriate controls on polluters.

The water quality problems directly caused by climate change could be exacerbated by other responses to climate change. Intensified agriculture in the region could increase runoff, necessitating more control of nonpoint sources of pollution. If agriculture in northern areas expands, surface and groundwater quality in relatively pristine areas may be degraded. Additional powerplants could add to pollution problems through the use of more cooling water. Pollution control authorities such as the U.S. EPA may need to impose more comprehensive controls for those areas and should consider this in their long-term planning.

Fisheries

Although the analysis on fisheries indicates that fish populations in the Great Lakes would generally increase, maintaining fisheries may require intensive management. In productive areas, the possibility of introduction of new species could mean major changes in aquatic ecosystems. Fisheries management may be needed to maintain commercially and recreationally valuable species. The Great Lakes Fishery Commission may wish to consider the possible implications of climate change on valuable fisheries and management strategies to handle these possible changes. Additional pollution controls may be needed to help maintain fisheries in such areas as western and central Lake Erie.

Land Use

Shorelines

The potential changes in land availability and uses present opportunities and challenges. Lower lake levels would open up new beaches and potential areas for recreation and development, although high capital costs may be associated with developing them. These lands could be kept undeveloped to serve as recreational areas and as protection against fluctuating lake levels and erosion. Conversely, they could be developed to provide more housing and commercial uses. Building structures closer to the shorelines would make them more vulnerable to short-term rises in lake levels.

How these lands will be used will be decided by local and State governments as well as private shoreline property owners. Under the Coastal Zone Management Act, States may identify coastal zone boundaries and define permissible land (and water) uses (Baldwin, 1984). Thus, the act could be used to help manage the use of exposed shorelines.

Lower lake levels and less ice cover may also increase shoreline erosion, decreasing the value of shorelines and degrading water quality. The Great Lakes Basin is not included in the U.S. coastal barrier system, a program that denies Federal funds for development of designated erosion or flood-prone coastal barriers (Ray et al.).

Forestry

The potential decline in forests and northward shift in Great Lakes agriculture raise many land use issues. One important issue may be how to manage potentially large and rapid shifts in forest composition. To speed northward colonization, plantings of the species might be recommended along the advancing front of suitable climate. However, unsuitable soils and day lengths shorter than the species can tolerate might limit the success of such plantings. The forest industry may consider growing different types of species and producing wood for different uses, such as for furniture rather than for pulp and paper. Potential uses of new prairies or savannas could present challenges.

Agriculture

Although forests may decline, demand for more land for agriculture in northern areas may grow; however, Adams indicated this demand may be small and will depend on market forces and policies. Federal and State land managers as well as local zoning laws may need to consider that the demand for land use may change. Rules on these lands could have a major influence on how, if at all, the north is developed.

Demographic Shifts

This report does not study the demographics associated with climate change and cannot say whether people will migrate north along with warmer climates. A workshop on climate change and the Great Lakes region, conducted by Ray et al. and attended by Government representatives, academics, and citizens group representatives who have studied climate-related Great Lakes resources, concluded that populations from other regions of the United States could migrate to the Great Lakes. The region could have a more favorable climate than more southern areas. Although lake levels may fall, the lakes will still contain a large amount of freshwater while other areas have more severe water availability problems. Consequently, the Great Lakes may be relatively more attractive than other regions.

Like lower lake levels, an in-migration could present opportunities and challenges. Such a migration could revitalize the region, reversing population and economic losses of recent decades. However, it also could exacerbate some of the problems associated with climate change. More people and industries would require more water and add more pollution, further stressing water supplies and quality. Population growth could increase pressure to develop exposed shorelines along the lakes.

CONCLUSION

Climate change could significantly alter the character of the region. It will be costly to respond to and will require new rules and laws. Some changes, such as loss of forests and dependent wildlife, may be irreversible. The lakes are a precious resource and may become even more valuable when climate changes. Maintaining their quality may require careful management of supplies and strengthened efforts at limiting pollution. Preserving forests and wildlife in a rapidly changing climate also may be difficult for planners. The challenge for the Great Lakes region will be to maintain the quality of the lakes and the surrounding land in response to climate change and the pressures it brings.

Chapter 5

REFERENCES

Assel, Raymond A. C.R. Snider, and R. Lawrence. 1985. Comparison of 1983 Great Lakes winter weather and ice conditions with previous years. Monthly Weather Review Vol. 113.

Baldwin, M.F. 1984. The Federal Government's role in the management of private rural land. Unpublished paper. p. 22.

Blumberg, A.F., and G.L. Mellor. 1983. Diagnostic and prognotic numerical circulation studies of the South Atlantic Bight. Journal of Geophysical Research 88:4579-4592.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1972. Rationale, limitations and assumptions of a northeast forest growth simulator. IBM Journal of Research and Development 16:101-116.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1973. Estimating the effects of carbon fertilization on forest composition by ecosystem simulation. In: Woodwell, G.M., and E.V. Pecan, eds. Carbon and the Biosphere. Brookhaven National Laboratory Symposium No. 24. Oak Ridge, Tennessee: USAEC, pp. 328-344.
Cobb, C.E. Jr. 1987. The Great Lakes' troubled waters. National Geographic 172(1):2-31.

Cohen, S.J. 1986. The effects of climate change on the Great Lakes. In: Titus, J.G., ed. Effects of Changes in Stratospheric Ozone and Global Climate, Vol. 3. United Nations Environment Programme, U.S. EPA. pp. 163-183.

Cohen, S.J. 1987. Projected increase in municipal water use in the Great Lakes due to CO_2 induced climate change. Water Resources Bulletin 23(1). pp. 91-101.

Croley, T.E. II. 1983a. Great Lakes basins (U.S.A. toCanada) runoff modelling. Journal of Hydrology 64:135-158.

Croley, T.E. II. 1983b. Lake Ontario Basin (U.S.A. toCanada) runoff modeling. Journal of Hydrology 66:101-121.

Croley, T.E. II. 1988. Lumped Modeling of Laurentian Great Lakes Evaporation, Heat Storage and Energy Fluxes for Forecasting and Simulation. NOAA Technical Memo, ERL GLERL-XX, Environmental Research Laboratories, Boulder, Colorado. (In press.)

Crowder, L.B., and J.J. Magnuson. 1983. Cost-benefit analysis of temperature and food resource use: a synthesis with examples from fishes. In: Aspey, W.P., and S.I. Lustick, eds. Behavioral Energetics. Ohio State University Press. Columbus, Ohio. pp. 189-221.

Crowe, R.B. 1985. Effect of Carbon Dioxide Warming Scenarios on Total Winter Snowfall and Length of Winter Snow Season in Southern Ontario. Atmospheric Environment Service - Canada. (Unpublished manuscript.)

Delay, W.H., and J. Seaders. 1966. Predicting temperatures in rivers and reservoirs. Journal of Sanitary Engineering 92:115-134.

DiToro, D.M., and J.P. Connolly. 1980. Mathematical Models of Water Quality in Large Lakes. Part 2: Lake Erie. Duluth, Minnesota: U.S. EPA. U.S.EPA -600/3-80-065.

DiToro, D.M., N.A. Thomas, C.S. Herdendorf, R.P. Winfield, and J.P. Connolly. 1987. A post audit of a Lake Erie eutrophication model. Journal of Great Lakes Research 134(4):801-825.

Edison Electric Institute. 1987. Statistical Yearbook of the Electric Utility Industry/1986. No. 54.
Eliot, J.L. 1985. A North Woods Park Primeval: Isle Royal. National Geographic. Vol. 167; No. 4 pp.534-550.

Environment Canada. 1987. Implications of Climate Change for Navigation and Power Generation in the Lakes. Climate Change Digest CCD 87-03.

Federal Reserve Bank of Chicago & The Great Lakes Commission. 1985. The Great Lakes Economy: A Resource and Industry Profile of the Great Lakes States. Boyne City, MI: Harbor House Publishers, Inc.

Garwood, R.W. Jr. 1977. An oceanic mixed layer capable of simulating cyclic states. Journal of Physical Oceanography 7:455-468.

Great Lakes Basin Commission. 1975. Great Lakes Basin Framework Study: Appendixes 5, 11, 12, 13, and 19. Ann Arbor, MI: Public Information Office. Great Lakes Basin Commission.

Horvath, F.J., M.R. Jannereth, and C.A. Shafer. 1988. Impacts of Water Level Fluctuations. Water Science and Technology Board Colloquium Series, Great Lake Water Levels: Shoreline Dilemmas. Chicago, Illinois.

International Joint Commission. 1985. Great Lakes Diversions and Consumptive Uses. Report by International Great Lakes Diversion and Consumptive Uses Study Board.

Jones, C.A. and J.R. Kiniry, eds. 1986. CERES-Maize: A simulation of maize growth and development. College Station, Texas: Texas A&M Press.

Kitchell, J.F., D.J. Stewart, and D. Weininger. 1977. "Applications of a bioenergetics model to yellow perch (Perca flavescens) and walleye (Stizostedion Vitreum vitreum). Journal of Fish Research 34:1922-1935.

Land Evaluation Group. 1986. Implications of Climatic Change and Variability for Ontario's Agri-food Sector. Prepared for Atmospheric Environment Service, Environment Canada. LEG-26.

Larsen, C.E. 1985. Lake Level, Uplift, and Outlet Incision, the Nipissing and Algoma Great Lakes. Quaternary Evolution of the Great Lakes: Geological Association of Canada Special Paper 30.
Linder, K.P., M.J. Gibbs and M.R. Inglis. 1987. Potential Impacts of Climate Change on Electric Utilities. New York State Energy Research and Development Authority, Albany, NY. Report 88-2.

Magnuson, J.J., L.B. Crowder, and P.A. Medvicle. 1979. "Temperature as an ecological resource." American Zoology 19:331-343.

Meisner, D.J. et al. 1987. An Assessment of the Effects of Climate Warming on Great Lakes Basin Fishes. J. Great Lakes Research 13(3):340-352.

Nekvasil, G.G. 1988. Lake Carriers Association, Personal Communication; June 16.

The New York Times. 1988. p. 16. June 15.

Quinn, F.H. 1987. Hydrologic response model of the North American Great Lakes. Journal of Hydrology 37:295-307.

Quinn, F.H. 1988. Fluctuations of Great Lakes Water Levels. Water Science and Technology Board Colloquium Series, Great Lakes Water Levels: Shoreline Dilemmas. Chicago, Illinois.

Conversation with Frank Quinn, Great Lakes Environmental Research Lab (October, 1987).

Conversation with David Rind, Goddard Institute for Space Studies (January, 1988).

Ruttner, F. 1931. Hydrographische und hydrochemische Beobachtungen auf Java, Sumatra und Vali. Archiv for Hydrobiologic Supplement. 8:197-454.

Solomon, A.M., and D. West. 1986. Atmospheric Carbon Dioxide Change: Agent of Future Forest Growth or Decline?" In: Titus, J., ed. Effects of Changes in Stratospheric Ozone and Global Climate. United Nations Environment Program/U.S. Environmental Protection Agency. Washington, D.C. pp. 23-38.

Tarlock, D.A. 1988. Multi-Jurisdictional Issues" Presented to National Research Council, Water Science Technology Board Colloquium Series, Great Lakes Water Levels: Shoreline Dilemma. Chicago, Illinois. March, 1980.

U.S. Bureau of the Census. 1987. Statistical Abstract of the United States: 1987. (107th edition) Washington, D.C.
U.S. Department of Commerce, Bureau of the Census. 1983. 1982 Census of Agriculture: Geographic Area Series.

U.S. Department of Agriculture, 1987. Agricultural Statistics. Washington, D.C.: U.S. Government Printing Office.
USDA Forest Service. 1982. An analysis of the timber situation in the U.S. 1952-2030. Forest Resource Report No. 23.

U.S. EPA and Environment Canada. 1987. The Great Lakes: An Environmental Atlas and Resource Book.

Wall, G. 1985. Climate Change and its Impact on Ontario Tourism and Recreation. Submitted to Environment Canada.

DRAFT

CHAPTER 6

SOUTHEAST

FINDINGS

Global climate change could affect the Southeast by causing forests to shift to grasslands, reducing agricultural productivity and increasing the abandonment of farms, diminishing fish and shellfish populations, and increasing electricity demand higher than the national average. Approximately 90 percent of the national coastal wetland loss and two-thirds of the national shoreline protection costs due to climate change could occur in the Southeast. The impacts on rivers and water supplies are uncertain.

Agriculture

- Southeastern agriculture is generally more vulnerable to heat stress than to freezing, so the adverse impacts of more hot days would offset a longer growing season.
- Due to climate change alone, yields of soybeans and corn would vary from no change in the cooler regions to up to a decrease of 91 percent in warmer areas, even if rainfall increases. When climate and the direct effects of CO_2 are considered, yields still drop in states such as Alabama and Mississippi due to extreme temperatures. Elsewhere, if rainfall rises, yields may increase. Increased CO_2 could also affect weeds, but these impacts were not analyzed.
- If rainfall decreases, irrigation would become necessary for farming to remain viable in much of the region.
- The range of such agricultural pests as potato leafhoppers, sunflower moths, and black cutworms could move north by a few hundred kilometers. This would most likely result in changes in the uses of pesticides.
- Considering various scenarios of climate change and CO_2, the productivity of southeastern agriculture could decline relative to northern areas, and 10 to 50 percent of the region's farmland could be withdrawn from cultivation. The decline in cultivated acreage may tend to be concentrated in areas where farming is currently marginally profitable.

Forests

- There may be a significant dieback in southern forests. Higher temperatures and drier soils may make it impossible for most species to regenerate naturally and may cause forests to convert to grassland. The decline in the forests could be noticeable in 30 to 80 years depending on the site and scenario. Southern non-coastal areas, such as Atlanta and Vicksburg, may have particularly large reductions. Relatively cool northern forests, such as those in Tennessee, may survive, although with some losses.

- The forest industry, which has infrastructure in main coastal areas and which is structured around currently valuable tree species, would have to either move or invest in new commercial tree species.

- Historically, abandoned farms have generally converted to forests. If large portions of the Southeast can no longer support the natural generation of forests, the character of the Southeast's landscape could gradually resemble that of the Great Plains.

Water Supplies

- Whether river flows and water supplies in the Southeast would increase or decrease cannot be determined because of uncertainties in precipitation and minimal snow pack. Water supply is very important for agricultural, recreational, and industrial uses. Any decrease in rainfall could disrupt recreation, hydropower, power plant cooling, and dilution of effluent, while more rainfall could increase the risk of flooding.

- For the scenarios used in this report, changes in operating rules for managed water systems would allow current water demands to be met in some instances.

Sea Level Rise

- A one-meter rise in sea level by the year 2100 would inundate 30 to 90 percent of the region's coastal wetlands and flood 2,600 to 4,600 square miles of dry land, depending on the extent to which people erect levees to protect dry land from inundation. Louisiana alone would account for 40 percent of national wetland loss, assuming current river management practices continue.

- Holding back the sea by pumping sand or other measures to raise barrier islands and protecting mainland areas with bulkheads and levees, for a one-meter rise would cost approximately $42 to $75 billion by the year 2100.

Marine Fisheries

- Gulf Coast fisheries could be negatively affected by climate change. A loss of coastal wetlands due to sea level rise could eliminate critical habitats for shrimp, crab, and other commercially important species. Warmer temperatures in the Gulf Coast estuaries will be at or above the thermal tolerances for commercially important finfish and shellfish, such as shrimp, flounder, and oysters. Oysters and other species could be threatened by the increased salinity that will accompany sea level rise.

Electricity Demand

- The annual demand for electricity in the Southeast could rise by 14 to 22 billion kilowatt hours (2 to 3 percent) by 2010 and by 100 to 197 BKWH (7 to 11 percent) by 2055 because of increased temperature.

- By 2010, approximately 7 to 16 gigawatts would be needed to meet the increased demand, and by 2055, 56 to 115 GW would be needed -- a 24 to 34 percent increase over baseline additions that may be needed without climate change -- the cumulation costs would be $77 to $110 billion by 2055.

Policy Implications

- Federal laws constrain the Corps of Engineers and other water resource managers from rigorously considering trade-offs between many nonstatutory objectives of federal dams in the Southeast, including recreation, water supply, and environmental quality. Increased flexibility would improve the ability of these agencies to respond to and prepare for climate change.

- Strategies now being evaluated by the Corps of Engineers to protect coastal wetlands in Louisiana may need to consider a sea level rise of 0.5 to 2.0 m in order to prevent wetlands from being lost. Measures that would enable this ecosystem to survive would require major changes in federal navigation and river flow policies.

- Given the potentially important impacts on forests, agencies such as the U.S. Forest Service and state agencies, and private companies may wish to assess the potential for large losses of southern forests and the implications for research and management strategies.

CLIMATE AND THE SOUTHEAST

The climate and the coastal zone of the Southeast are among the chief factors that distinguish the southeastern United States from the rest of the nation.* The warm temperatures, abundant rainfall, and generally flat terrain gave rise in the 17th century to a strong agricultural economy with a distinctive regional culture. The combination of a benign climate and 60% of the nation's ocean beaches continues to attract both tourists and new residents to the southeastern coastal plain. Florida, for example, is the nation's fastest growing state and will be the third largest by the year 2000. (Meo, Volume _).

The projected change in climate, however, could severely disrupt life in this region. Cities that already are unpleasantly hot during the summertime would become hotter, with corresponding increases in air-conditioning demands and electric bills. Fisheries would be threatened by the hotter estuarine temperatures and the loss of coastal wetlands. Rising sea level would erode beaches, inundate wetlands, exacerbate coastal flooding, and increase the salinity of estuaries, aquifers, and wetlands.

CLIMATE SENSITIVE RESOURCES OF THE SOUTHEAST

Water Resources

When statewide averages are considered, each of the seven states in the Southeast receives more rainfall than any other state in the continental United States. Moreover, the rivers of the Southeast drain over 62% of the nation's lands, with the Mississippi River draining 38% of the nation (Geraghty et al., 1973).

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*Except for the discussion of the economic implications for agriculture, the term "Southeast" refers to the study area shown in Figure 6-1: North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Tennessee, and the coastal zones of Louisiana and Texas.

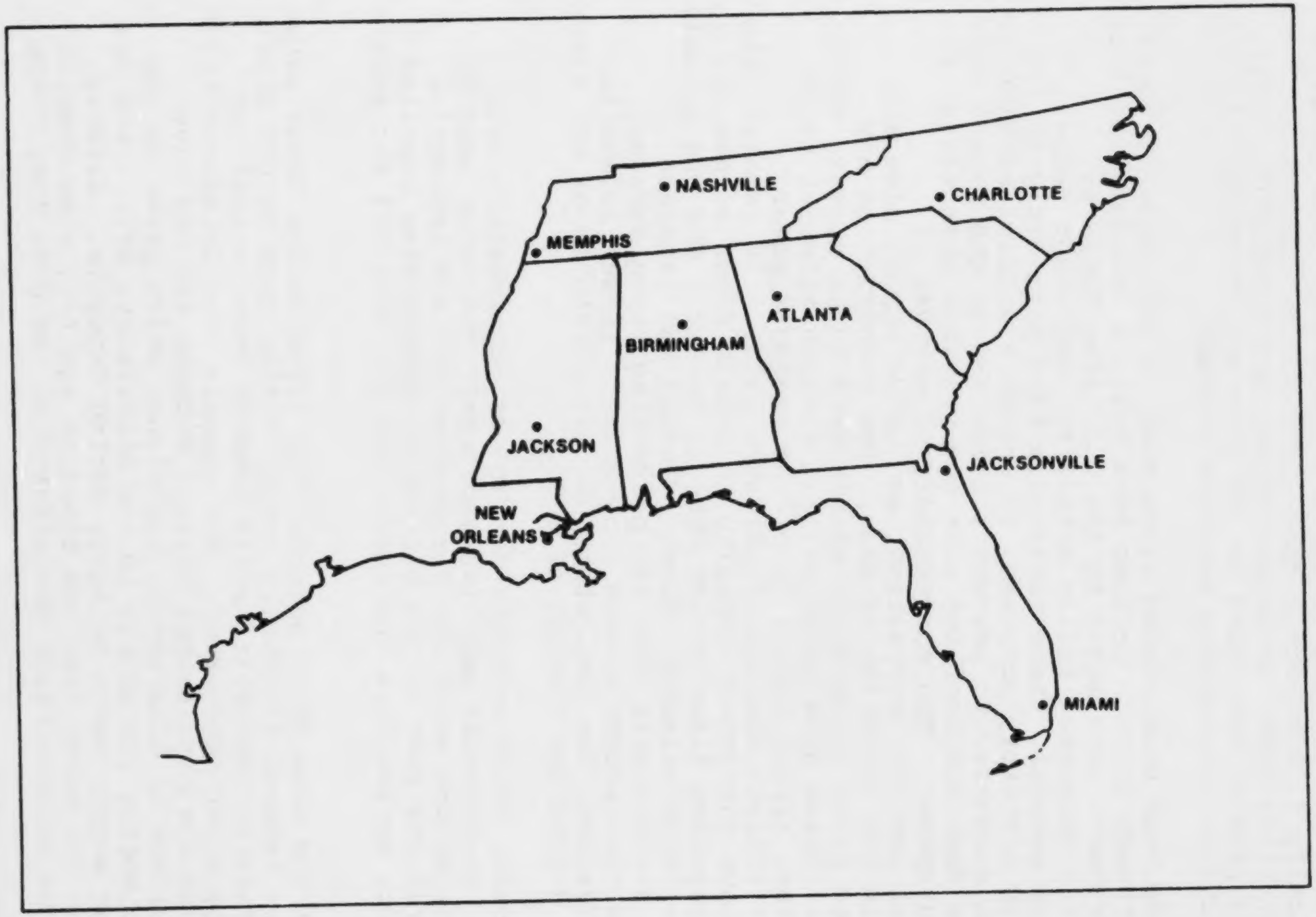

NASHVILLE
CHARLOTTE
MEMPHIS
ATLANTA
BIRMINGHAM
JACKSON
JACKSONVILLE
NEW ORLEANS
MIAMI

Figure 6-1. Southeast region

Southeast

The Southeast supports 50,000 square miles (mi^2) of bottomland hardwood forests (Mitch and Gosselink, 1986),[**] which are periodically flooded areas that offer winter habitat formigratory birds such as ducks, geese, and songbirds. Bass, catfish, and panfish are found in the slow-moving rivers, and trout inhabit the fast-moving mountain streams.

Dams have been constructed along most of the region's major rivers. Although private parties have built a few dams, most of the major projects were built by the U.S. Army Corps of Engineers, the Tennessee Valley Authority, and other federal agencies. In general, these reservoirs have been designed for the following statutory purposes: to ensure a sufficient flow of water during droughts; to prevent floods; and to the extent that this purpose does not conflict with the previous objectives, to generate hydropower. The nonstatutory objectives of environmental quality, recreation, and water supply also are considered in the operation of dams. Dam construction has created large lakes along which people have built houses, hotels, and marinas. These dams generate 22.2 billion kilowatt hours (kWh) per year, approximately 7% of the region's power requirements (Edison Electric Institute, 1985). In general, the reservoirs have sufficient capacity to retain flood surges and to maintain navigation flows during the dry season. The one notable exception is the Mississippi River: levees and land-use regulations are the main toos for preventing flood damages; although the Mississippi's base flow usually is sufficient to support navigation, the navigation on navy stretches of the river was impeded during the drought of 1988.

In Florida, which accounts for 45% of southeastern water consumption, groundwater supplies about half the water used by farms and 85% of the water use for residential and industrial purposes. For the rest of the Southeast, groundwater supplies most water for agriculture and rural uses but only 30% for public supplies.

Atlanta and some other metropolitan areas derive their water supplies from Federal reservoirs. Many cities that do not obtain water from Federal reservoirs still benefit from Federal and Federal/State water management. For example, New Orleans obtains its water from the Mississippi River. Without the Old River Control Structure in Simmesport, Louisiana, which prevents the river from changing its course to the Atchafalaya River, the New Orleans water supply would be salty during droughts. Although Miami obtains its water from the Biscayne aquifer, some coastal wells would be salty without the efforts of the U.S. Army Corps of Engineers and the South Florida Water Management District to recharge the aquifer with supplemental freshwater from canals and Lake Okeechobee.

[**] This measure includes MS, AK, LA, TX, and VA.

The various uses of water often conflict with each other. Hydroelectric power generators and lakefront property and boat owners benefit when water levels are maintained as high as possible. However, high water levels make flood control more difficult, and summer releases for navigation, hydropower, and environmental quality require that lake levels be lowered during the dry season.

Estuaries

Over 43% of the fish and 70% of the shellfish harvested in U.S. waters are caught in the Southeast (Fishery Statistics Division, NOAA, 1987). Commercially important fishes are abundant largely because over 85% of the nation's coastal wetlands are found in this region; over 40% are found in Louisiana alone.

Most of the wetlands in the Southeast are less than 1 meter (m) above sea level. The wetlands in Louisiana are already being lost to the sea at a rate of 50 mi^2 per year due to the interaction of human activities and current rates of relative sea level rise resulting from the delta's tendency to subside 1 cm per year.

Summer temperatures in many of the gulf coast estuaries are almost as warm as crabs, shrimp, oysters, and other commercially important fishes can tolerate (Livingston, Volume__). Winter temperatures along the Gulf coast are almost warm enough to support mangrove swamps, which generally replace marshes once they are established; mangroves already dominate the Florida coast south of Fort Lauderdale.

Beach Erosion and Coastal Flooding

The Southeast has 1,100 miles of sandy ocean beaches, many of which are found on low and narrow barrier islands. The Atlantic coast is heavily developed; while much of the gulf coast is only now being developed. In part because of their vulnerability to hurricanes, none of Mississippi's barrier islands has been developed, only one of Louisiana's barrier islands has been developed. Because much of Florida's gulf coast is marsh, it is still largely undeveloped.

All eight coastal states are experiencing coastal erosion. Along developed coasts, recreational beaches have narrowed, increasing the vulnerability of shorefront structures to storms. In Louisiana, some undeveloped barrier islands are eroding and breaking up. Elsewhere, narrow barrier islands are keeping pace with sea level rise by "overwashing" (i.e., rolling over like a rug) in a landward direction, while wide islands and mainland coasts have simply eroded. The coastal states of the Southeast are responding by holding back the sea in some areas and by adapting to erosion in others.

The two greatest natural disasters in U.S. history resulted from floods associated with hurricanes in Galveston, Texas, and Lake Okeechobee, Florida, in which over 8,000 people drowned. After the Mississippi River overflowed its banks and inundated most of coastal Louisiana in the 1930s, Congress directed the Corps of Engineers to initiate a major Federal program of flood control centered around the Southeast. Nevertheless, flood waters often remain over some low areas in Louisiana and Florida for several days after a major rainstorm.

Hurricanes continue to destroy recreational development in at least a few ocean beach communities almost every year in the Southeast. The region presently experiences the majority of U.S. coastal flooding and probably would sustain the worst increases in flooding as a result of global warming. Unlike the Northeast and Pacific coasts, this region has wide low-lying coastal plains and experiences several hurricanes annually. Each year, storms destroy recreational development in at least a few ocean beach communities. Florida, Texas, and Louisiana account for 62% of the $144 billion of private property insured by the Federal Flood Insurance Program.

Agriculture

In the last few years, droughts and heat waves have caused crop failures in many parts of the Southeast. Unlike many of the colder regions, cold weather is generally not a major constraint to agricultural production, except for Florida's citrus industry.

Although cotton and tobacco were once the mainstays of the Southeast's economy, agriculture now accounts for only 1% of the region's income (Bureau of Economic Analysis, 1986). Since World War II, substantial amounts of farmland have been withdrawn from agriculture, and much of this land has been converted to forest. The cotton crop has largely been lost to the irrigated Southwest, and although tobacco remains profitable, it is grown on only 1/2 million acres. However, in the last few decades, southeastern farmers have found soybean growth to be profitable; soybeans now account for 45% of all cultivated land in the Southeast. Corn

Table 6-1. Annual Revenues by State for Various Crops.

Crop	Value ($1,000)
Corn for Grain	
Alabama	56,550
Florida	31,493
Georgia	203,931
Mississippi	22,600
North Carolina	324,789
South Carolina	104,333
Tennessee	193,687
Cotton	
Alabama	145,540
Florida	8,112
Georgia	97,325
Mississippi	449,630
North Carolina	30,944
Tennessee	109,610
Sugarcane for sugar and seed	
Florida	369,899
Tobacco	
Florida	NA
Georgia	NA
North Carolina	NA
South Carolina	NA
Tennessee	NA
Peanuts for Nuts	
Alabama	133,930
Florida	48,600
Georgia	472,645
North Carolina	122,941
South Carolina	5,882
Soybeans	
Alabama	140,719
Florida	31,036
Georgia	179,676
Mississippi	365,018
North Carolina	196,673
South Carolina	125,214
Tennessee	230,373

Source: U.S. Department of Agriculture, Agricultural Statistics: 1987, pp. 32, 34, 62, 63, 80, 93, 121, 126, 127.

continues to account for 5% of southeastern agriculture (Bureau of the Census, 1982). Table 6-1 compares annual revenues by state for various crops.

Forests

The commercial viability of southeastern forests has increased greatly since World War II, primarily due to the increased use of softwoods, such as pines and firs for plywood and uses that once required hardwood. Because this transition coincided with lower farm prices and declining soils in the piedmont foothills of the Southeast, many mountain farms have been converted to forests. Conversely, in the last 10 years, 7 million acres of coastal plain forests have been converted to agriculture (Healy, 1985).

Approximately 45% of the nation's softwood (mostly loblolly pine) and 50% of its hardwood are grown in the region. Forests cover 60% of the Southeast, and 90% of forests are logged. Oak-hickory covers 35%, and pine covers another 33% of commercial forests. Only 9% of the southeastern forests are owned by the Federal and state governments, and 18% are owned by the forest industry. In contrast, 73% of the forests are owned by farmers and other private parties (Healy, 1985).

Indoor and Outdoor Comfort

The Southeast is one of the few areas that spends as much money on air-conditioning as on heating. Figure 6-2 shows temperatures throughout the Southeast for the months of January, April, July, and October. Even in January, about half the region experiences average temperatures above 50°F, and almost the entire region has a typical daily high above 50°F. Thus, with the possible exception of the mountains of Tennessee and North Carolina, a global warming would increase the number of days during which outdoor temperatures would be unpleasantly warm.

PREVIOUS STUDIES OF THE IMPACTS OF CLIMATE CHANGE ON THE SOUTHEAST

Most studies examining the impact of global warming on the Southeast have focused on sea level rise. Recent efforts have addressed other topics.

Flooding

Leatherman (1984) and Kana (1984) applied flood-forecasting models to assess the potential increases in flooding in Galveston, Texas, and Charleston, South Carolina. For the

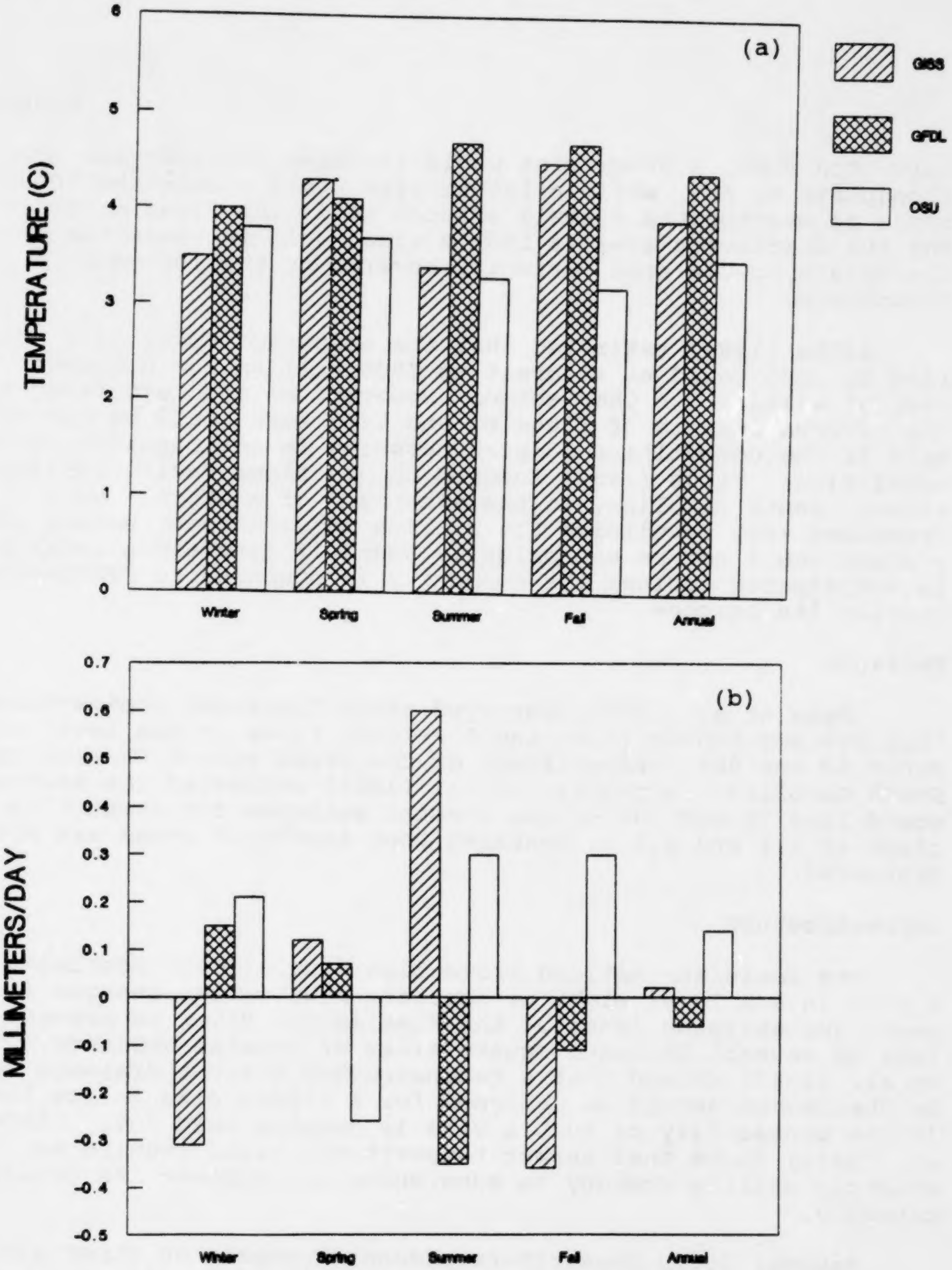


Figure 6-2. Climate scenarios for the Southeast, (a) temperature and (b) precipitation.

Galveston area, a 90-cm rise would increase the 100-year floodplain by 50%, while a 160-cm rise would enable the 100-year strom to overtop the seawall erected after the disaster of 1900. For the Charleston area, a 160-cm rise would increase the 10-year floodplain to the area currently covered by the 100-year floodplain.

Gibbs (1984) estimated that the economic impact of a 90-cm rise by 2075 could be as great as $500 million for Galveston and over $1 billion for Charleston. However, he also estimated that the adverse impacts of flooding and land loss could be cut in half if the communities adopted measures in anticipation of sea level rise. Titus (1984) focused on decisions facing Sullivans Island, South Carolina, in the aftermath of a storm. He concluded that rebuilding $15 million in oceanfront houses after a storm would not be economically sound if future sea level rise is anticipated, unless the community is prepared to continuously nourish its beaches.

Wetlands

Kana et al. (1986) surveyed marsh transects and estimated that 90- and 160-cm (3.0- and 5.2-foot) rises in sea level would drown 50 and 90%, respectively of the marsh around Charleston, South Carolina. Armentano et al. (1988) estimated the Southeast would lose 35 and 70% of its coastal wetlands for respective rises of 1.4 and 2.1 m, assuming that developed areas are not protected.

Infrastructure

The Louisiana Wetland Protection Panel (1987) concluded that a rise in sea level might necessitate substantial changes in the ports and shipping lanes of the Mississippi River to prevent the loss of several thousand square miles of coastal wetlands. Titus et al. (1987) showed that a reconstructed coastal drainage system in Charleston should be designed for a 1-foot rise in sea level if the probability of such a rise is greater than 30%. Linder et al. (1988) found that warmer temperatures would require an electric utility company to substantially increase its generating capacity.

Several dozen researchers presented papers on other global warming impacts on the Southeast at a 1987 EPA conference held in New Orleans (Meo, 1987). The proceedings include papers on forests, agriculture, coastal erosion, and water resources.

CLIMATE CHANGE STUDIES IN THIS REPORT

Table 6-2 and Figure 6-3 illustrate the studies undertaken as part of this effort. Models of coastal erosion, coastal wetland loss, agricultural yields, and electricity consumption were used to derive regionwide estimates. Efforts to estimate impacts on water resources, infrastructure, forests, and the ecology were limited to conducting illustrative case studies.

SCENARIOS OF FUTURE CLIMATE CHANGE

Figure 6-2 illustrates the scenarios of future climate change from general circulation models. Table 6-3 shows the more detailed seasonal changes.

Table 6-3 illustrates how the frequency of mild days during the winter and the frequency of very hot days during the summer might change under the Goddard Institute for Space Studies (GISS) doubled CO_2 scenario. These estimates used average monthly changes in temperature and assumed no change in the frequency or duration of temperature extremes. Under this scenario, the number of days per year in which the mercury would fall below freezing would decrease from 34 to 6 in Jackson, Mississippi; from 39 to 20 in Atlanta; and from 41 to 8 in Memphis. The number of winter days above 70°F would increase from 15 to 44 in Jackson, from 4 to 14 in Atlanta, and from 5 to 24 in Memphis.

Of the nine cities shown, only Nashville has summer temperatures that currently do not regularly exceed 80°F. However, the number of days with highs below 80°F would decline from 60 to 34. Elsewhere, the heat would be worse. The number of days per year above 90°F would increase from 30 to 84 in Miami, from 17 to 53 in Atlanta, and from 55 to 85 in New Orleans. Memphis, Jackson, New Orleans, and Jacksonville, which currently experience 0 to 3 days per year above 100°F, would have 13-20 such days (Kalkstein, Vol. _).

Coastal Impacts

A number of national studies for the report presented results for the effects of climate change on the southeastern coast. Leatherman estimated the cost of maintaining recreational beaches. Park et al. and Weggel et al. examined the impacts onwetland loss and shoreline defense, and used their results to estimate the regionwide cost of raising barrier islands.

Table 6-2. Studies of the Southeast

Regional Studies

- Impacts on Runoff in the Upper Chattaboochee River Basin -- Hains, C.F. Haines, Hydrologist, Inc.
- Projected Changes in Estuarine Conditions Based on Models of Long-Term Atmospheric Alteration -- Livingston, Florida State University.
- Policy Implications of Global Climatic Change Impacts upon the Tennessee Valley Authority Reservoir System, Apalachicola River, Estuary, and Bay and South Florida -- Meo, Ballard, Deyle, James, Malysa, and Wilson, University of Oklahoma.
- Potential Impacts on Climatic Change on the Tennessee Valley Authority Reservoir System -- Miller and Brock, Tennessee Valley Authority.
- Impact of Climate Change on Crop Yield in the Southeastern U.S.A. -- Peart, Jones, and Curry, University of Florida.
- Methods for Evaluating the Potential Impacts of Global Climate Change -- Sheer and Randall, Water Resources Management, Inc.
- Forest Response to Climate Change: A Simulation Study for Southeastern Forests -- Urban and Shugart, University of Virginia.

National Studies that Included Southeast Results

- The Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment. -- Adams, Glyer, and McCarl, Oregon State University.
- National Assessment of Beach Nourishment Requirements Associated with Accelerated Sea Level Rise -- Leatherman, University of Maryland.
- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates -- Linder and Inglis, ICF Inc.

- The Effects of Sea Level Rise on U.S. Coastal Wetlands -- Park and Trehau, Butler University.

- Potential Effects of Climatic Change on Plant-Pest Interactions -- Stinner, Rodenhouse, Taylor, Hammond, Purrington, McCartney, and Barrett, Ohio Agricultural Research and Development Center.

- An Overview of the Nationwide Impacts of Rising Sea Level -- Titus and Greene, U.S. Environmental Protection Agency.

- The Cost of Defending Developed Shorelines Along Sheltered Waters of the United States from a Two Meter Rise in Mean Sea Level -- Weggel, Brown, Escajadillo, Breen, and Doheny, Drexel University.

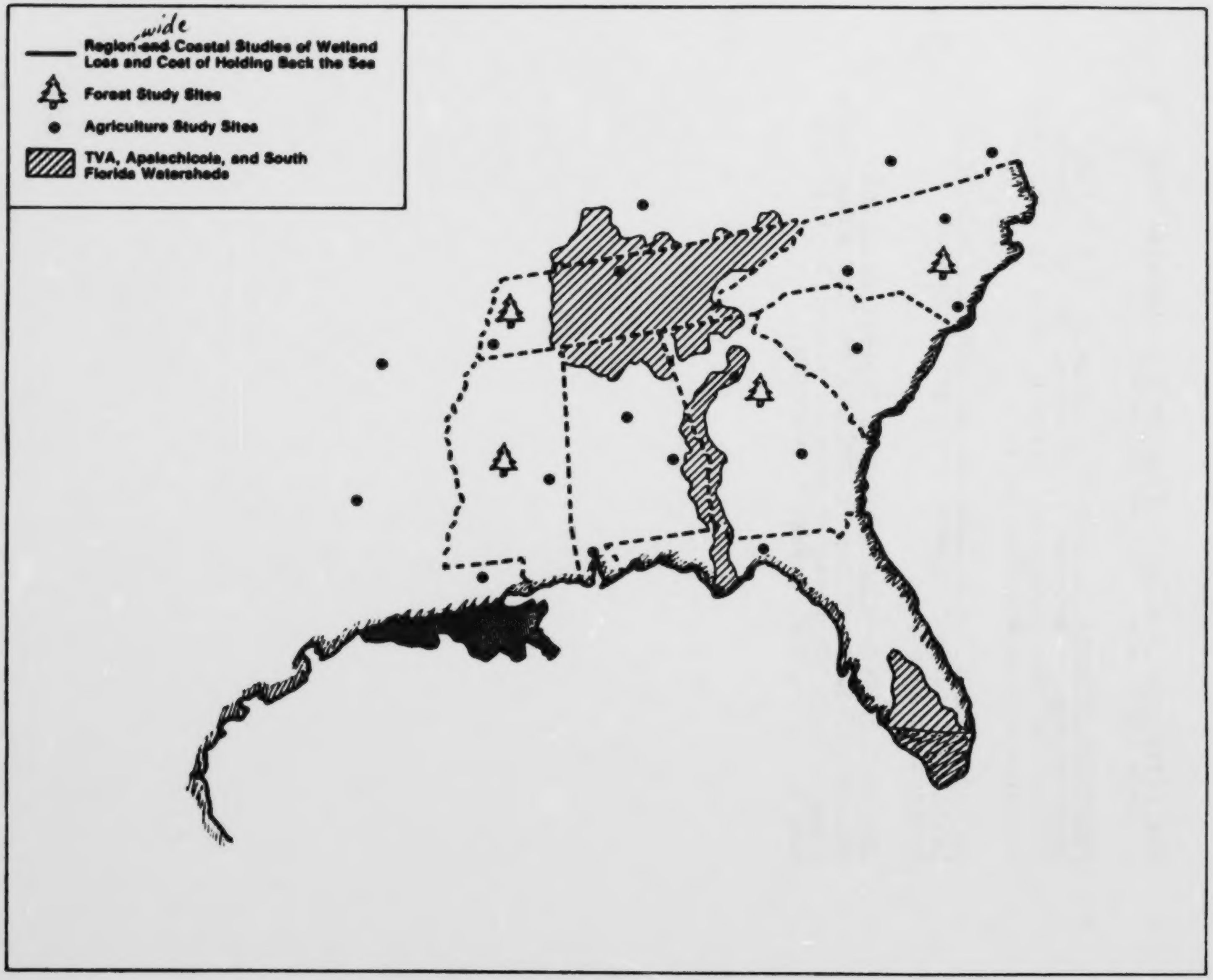

Region-wide and Coastal Studies of Wetland Loss and Cost of Holding Back the Sea
Forest Study Sites
Agriculture Study Sites
TVA, Apalachicola, and South Florida Watersheds

Figure 6-3. Overview of Southeastern Studies

Table 6-3. The GISS Doubled CO_2 Scenario: Frequency of Hot and Cold Days (°F)

	Number of Winter days with...				Number of Summer days with....					
	Daily Low <32		Daily High >= 70		Daily High <80		Daily High >90		Daily High >= 100	
YEAR	HIST	2xCO2	HIST	2xCO2	HIST	2xCO2	HIST	2xCO2	HIST	2xCO2
Atlanta, GA	38.3	20.5	4.2	13.6	10.0	2.2	17.1	53.3	0.6	4.2
Birmingham, AL	35.5	8.1	7.1	30.7	4.5	0.4	34.1	72.5	1.5	10.7
Charlotte, NC	42.1	23.8	3.4	9.9	11.9	3.7	23.1	56.5	0.1	5.9
Jackson, MS	33.5	5.9	15.3	43.5	0.8	0.2	55.1	83.1	2.0	19.5
Jacksonville, FL	9.3	1.7	34.6	49.6	2.3	0.3	46.4	81.3	0.6	14.1
Memphis, TN	41.2	8.1	5.2	23.6	4.9	0.7	50.5	74.8	2.6	19.1
Miami, FL	0.2	0.0	72.9	82.7	0.6	0.0	29.8	83.5	0.0	2.5
Nashville, TN	42.5	15.4	0.3	8.6	60.4	33.7	10.5	20.2	0.3	3.5
New Orleans, LA	14.9	3.5	24.9	39.5	0.9	0.1	55.4	84.9	0.3	13.5

The projected rise in sea level would cause shorelines to retreat, exacerbate coastal flooding, and increase the salinity of estuaries, wetlands, and aquifers. The nationwide study of sea level rise focused on retreating shorelines and the costs of holding back the sea. (See Chapter 9 for a discussion of the rationale, methods, and nationwide results of these studies.)

Coastal Wetlands

Park (Volume __) examined 29 southeastern sites to estimate the likely regionwide loss of coastal wetlands for a variety of scenarios of future sea level rise. His analyses included such societal responses as providing structural protection for all shorelines (total protection), protecting areas that are densely developed today (standard protection), and allowing shorelines to adjust naturally without coastal protection (no protection).

Figure 6-4 illustrates Parks's projections for the year 2100 for the various scenarios of sea level rise and coastal defense. Even if current sea level trends continue, 25% of the Southeast's coastal wetlands will be lost, mostly in Louisiana.

- current trends imply a loss of 15%;
- a 50-cm rise would result in a loss of 35 to 50%; depending on how shorelines are managed;
- a 100-cm rise results in losses of 45 to 68%; and
- a 200-cm rise implies losses of 63 to 80%.

Park et al. estimate losses of 50, 75, and 98% for Louisiana under the three scenarios. However, Park did not consider the potential for mitigating the loss by restoring the flow of river water into these wetlands. Titus and Greene estimated statistical confidence intervals illustrated in Table 6-4.

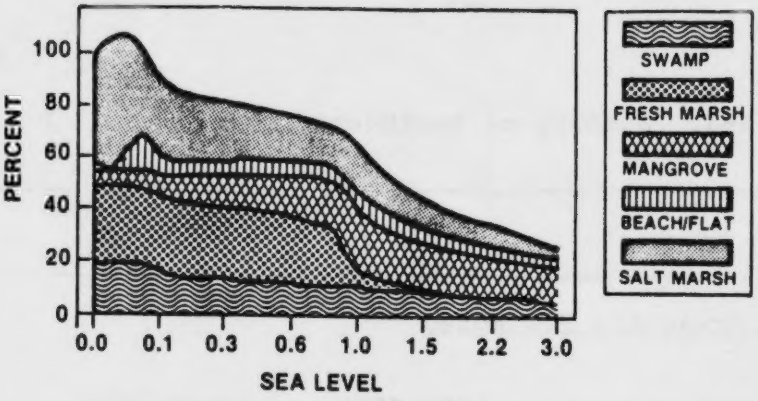
Total Coastal Land Loss

Park also estimated total land loss, including both wetlands and dry land. Most of the land loss from a rise in sea level would occur in Louisiana, as shown in Table 6-4. A 50-cm (20-inch) sea level rise would result in the loss of 1900-5900 mi^2 of land, while a 200-cm rise would inundate 10000-11000 mi^2.

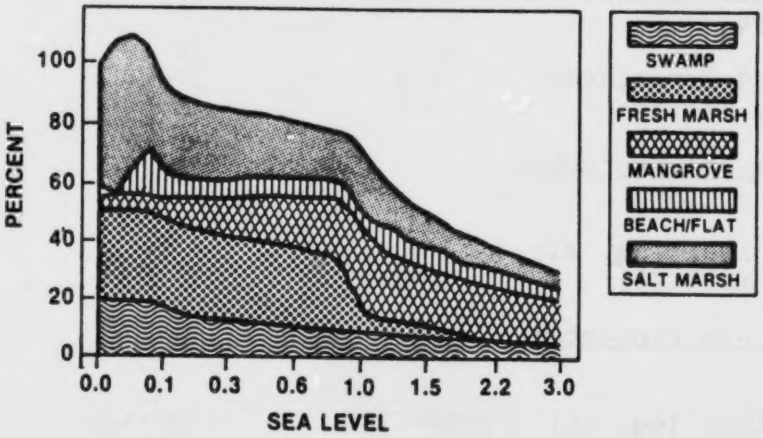
Cost of Protecting Recreational Beaches

In Volume___, Leatherman notes that the projected rise in sea level would threaten all developed recreational beaches. Even a 1-foot sea level rise would erode shorelines over 100 feet

A. NO PROTECTION



B. STANDARD PROTECTION



C. TOTAL PROTECTION

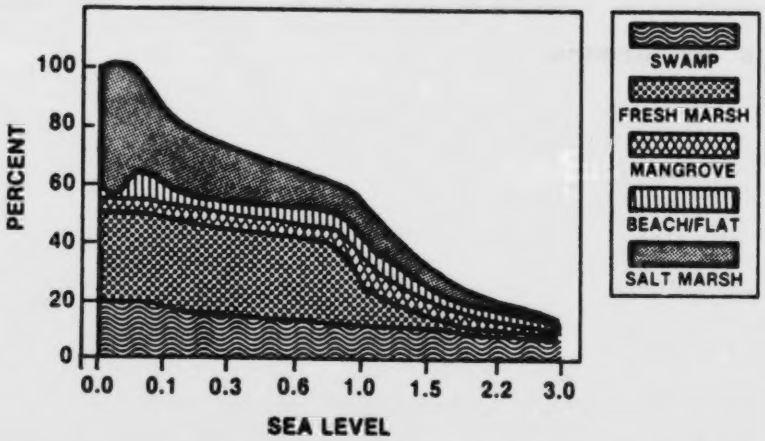


Figure 6-4. Southeastern Wetland Loss for Three Shoreline Protection Options

Source: Park et al., Volume _.

Table 6-4. Summary of Southeastern Results ($ billions)

	50	100	200
If Developed Areas Are Protected			
Land Lost			
Dryland Lost (sq. mi)	1900-5500	2600-6900	4200-10100
Wetlands Lost (%)	24-50	34-77	40-90
Cost of Coastal Defense	19-28	42-75	127-174
Open Coast			
Sand	10-15	19-30	44-74
Elevated Structures	5-9	10-40	60-75
Sheltered Shores	2-5	5-13	9-41
If All Shores Are Protected			
Land Lost			
Drylands Lost (sq. mi)	0	0	0
Wetlands Lost (%)	38-61	47-90	68-93
If No Shores Are Protected			
Land Lost			
Dryland Lost (sq. mi)	2300-5900	3200-7600	4800-10800
Wetlands Lost (%)	22-48	30-75	37-88

Source: Titus and Greene

throughout the Southeast. Along the coasts of North Carolina and Louisiana, the erosion would be considerably greater. (See Chapter 9 for a discussion of methods for estimating coastal erosion.) Because the distance from the high tide line to the first building is rarely more than 100 feet, most recreational beaches would be lost, unless either the buildings were removed or engineering measures were undertaken.

Table 6-4 illustrates Leatherman's estimates of the cost of protecting recreational beaches by pumping sand from offshore locations (see Chapter 9, Sea Level Rise for state by state results). A 1-m rise in sea level would imply almost $20 billion in dredging costs, with Texas spending $8.5 billion and Florida and Louisiana each spending over $3 billion.

Using constant unit costs (except for Florida), Leatherman estimated that a 2-m rise would only double the total cost to $43 billion. Titus and Greene estimated that if the unit costs of sand increased, 1- and 2-m rises would cost $30 and 74 billion, respectively. They also estimated that the cost of rebuilding roads and utilities on barrier islands would be 5-9, 10-40, and 60-75 billion for the three scenarios.

Cost of Protecting Calm-Water Shorelines

While Leatherman focused only on the open ocean coast, Weggel et al. estimated the regionwide costs of holding back the sea in developed sheltered and calm-water areas. Table 6-4 illustrates the estimated costs for the Southeast. Weggel et al. estimate that about $2 billion would be spent to raise roads and to move structures, and $23 billion would be spent to erect the necessary levees and bulkheads. The combined cost is $68-83 billion. These estimates do not include the costs of preventing flooding or of protecting water supplies.

Tennessee Valley Authority Studies

The Tennessee Valley Authority (TVA) was created in 1933 to spur economic growth in an area previously considered to be one of the nation's poorest. Geographically isolated by the Appalachian Mountains, the region lacked electricity and roads, and the Tennessee River could not provide reliable transportation because it flooded in the spring and dried to a trickle during the summer. By creating the TVA, Congress sought to remedy this situation by harnessing the river to provide electricity, to prevent the flooding that had plagued Chattanooga, and to ensure sufficiently stable riverflows that would permit maintenance of a 9-foot-deep navigation channel.

The region administered by the TVA covers 40,000 mi^2 and includes parts of seven states. In the last half century, the TVA has coordinated the construction of 43 major dams along the river and its tributaries, many of which are shown in Figure 6-5. The system provides power to over 7 million people, and contains 675 miles of navigable waterways with annual commercial freight of 28 million tons. The lakes created by the dams have over 10,000 miles of shoreline, which generate 75 million visits each year and along which people have invested $630 million. The lakes and streams generate 17 million visits per year, enough to indirectly boost the region's annual economy by $400 million (Miller and Brock).

To assess the potential impacts of climate change, Miller and Brock conducted a modeling study of the water resource implications, and Meo et al. examined the policy implications for the TVA.

TVA Modeling Study

Methods

Miller and Brock used the TVA's "Weekly Scheduling Model," on which the Agency currently bases its operations, to assess the impacts of climate change. This is a linear programming model that selects a weekly schedule for managing each reservoir in the TVA system by sequentially satisfying the objectives of flood control, navigation, water supply, power generation, water quality, and recreation. Miller and Brock used this model to simulate reservoir levels, riverflows, and hydropower generation for wet and dry scenarios, based on the runoff estimates from the GISS doubled CO_2 model run.*

Miller and Brock assessed the potential impacts of climate change on flood levels in Chattanooga, Tennessee, using a model that had been developed to estimate the constraints on weekly tributary releases. They also estimated the potential implications for water quality in the Upper Holston Basin of the valley, using a reservoir water quality model, a riverflow model, and a water quality model that TVA has used in the past to determine the environmental constraints affecting riverflow.

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*TVA used runoff from the GCMs, rather than hydrologic analysis, to estimate streamflow. The GISS scenario estimates high runoff. Since the Geophysical Fluid Dynamics Laboratory (GFDCL) and Oregon State University (OSU) scenarios estimated that no runoff the $1xCO_2$ and $2xCO_2$ runs, Miller and Brock used the inverse of GISS as a dry scenario (Rind, 1988)).

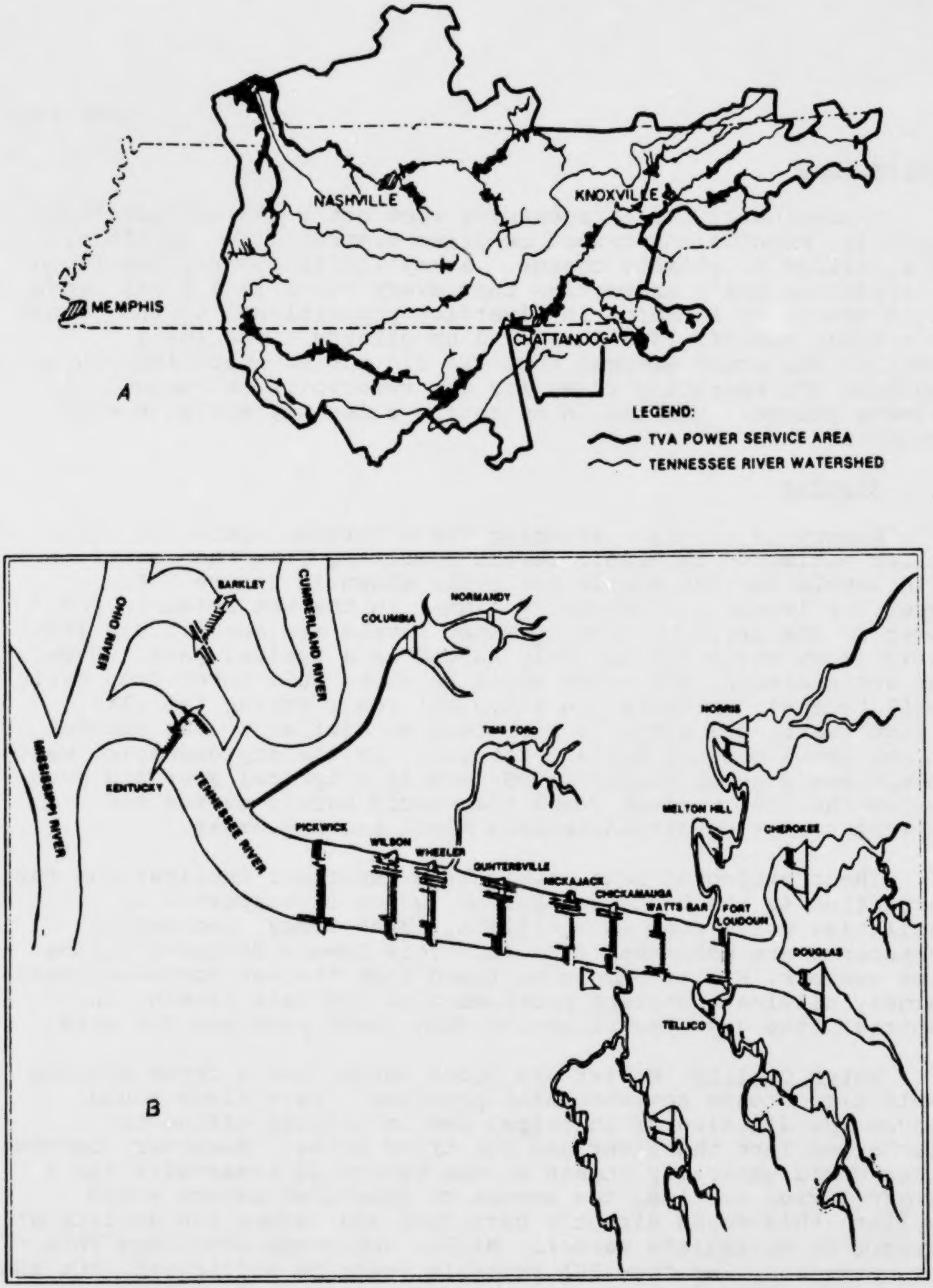
MEMPHIS
NASHVILLE
KNOXVILLE
CHATTANOOGA
A
LEGEND:
TVA POWER SERVICE AREA
TENNESSEE RIVER WATERSHED
BARKLEY
CUMBERLAND RIVER
OHIO RIVER
COLUMBIA
NORMANDY
MISSISSIPPI RIVER
KENTUCKY
TENNESSEE RIVER
TIMS FORD
NORRIS
MELTON HILL
CHEROKEE
PICKWICK
WILSON
WHEELER
GUNTERSVILLE
NICKAJACK
CHICKAMAUGA
WATTS BAR
FORT LOUDOUN
DOUGLAS
TELLICO
B

Figure 6-5. (a) Map of the TVA region and (b) schematic of the TVA reservoir system (b).

Source: Tennessee Valley Authority

Limitations

Since the riverflow scenarios were not based on hydrologic analysis, conclusions cannot be drawn regarding the sensitivity of riverflow to climate change. A key limitation for the flood analysis was EPA's assumption that every storm in a given month would result in a change in riverflow proportional to the change in monthly runoff. (See Chapter 3 on climate scenarios.) Finally, the study assumed that TVA did not mitigate impacts by changing its operating rules for the reservoirs in response to climate change. Changes in operating rules may mitigate some impacts.

Results

Reservoir levels. Assuming TVA's current operating rules, Miller estimated reservoir levels resulting from the scenarios, with levels for the Norris reservoir shown in Figure 6-6. Reservoir levels are generally higher in the wet scenario and lower in the dry. Currently, water levels are above 1,010 feet (NLVD) from early May to early August in a typical year. Under the wet scenario, the water would be above this level from early April to early September in a typical year; during the (1%) driest years, the water levels would be similar to the current normal level between May and October. In the dry scenario, water levels would never exceed 1,005 feet in a typical year and even during the (1%) wettest years they would barely exceed the current normal condition between April and September.

These projected lake levels have important implications for recreation in the Tennessee Valley, which is supported by facilities worth over $600 million. Even today, recreation proponents are concerned with reservoir levels dropping during some summers. Miller and Brock found that the wet scenario would largely eliminate current problems with low lake levels; in contrast, the dry scenario would make these problems the norm.

Water Quality. Miller and Brock found that a dryer climate could also create environmental problems. Lower flows would reduce the dilution of municipal and industrial effluents discharged into the river and its tributaries. Moreover, because water would generally remain at the bottom of reservoirs for a longer period of time, the amount of dissolved oxygen would decline; this would directly harm fish and reduce the ability of streams to assimilate wastes. Miller and Brock concluded that the water supplies from TVA probably would be sufficient, but the TVA could experience operational difficulties and customer dissatisfaction due to degraded water quality. During extended low-flow conditions, wastes would have increased opportunities to backflow upstream to water supply intakes.

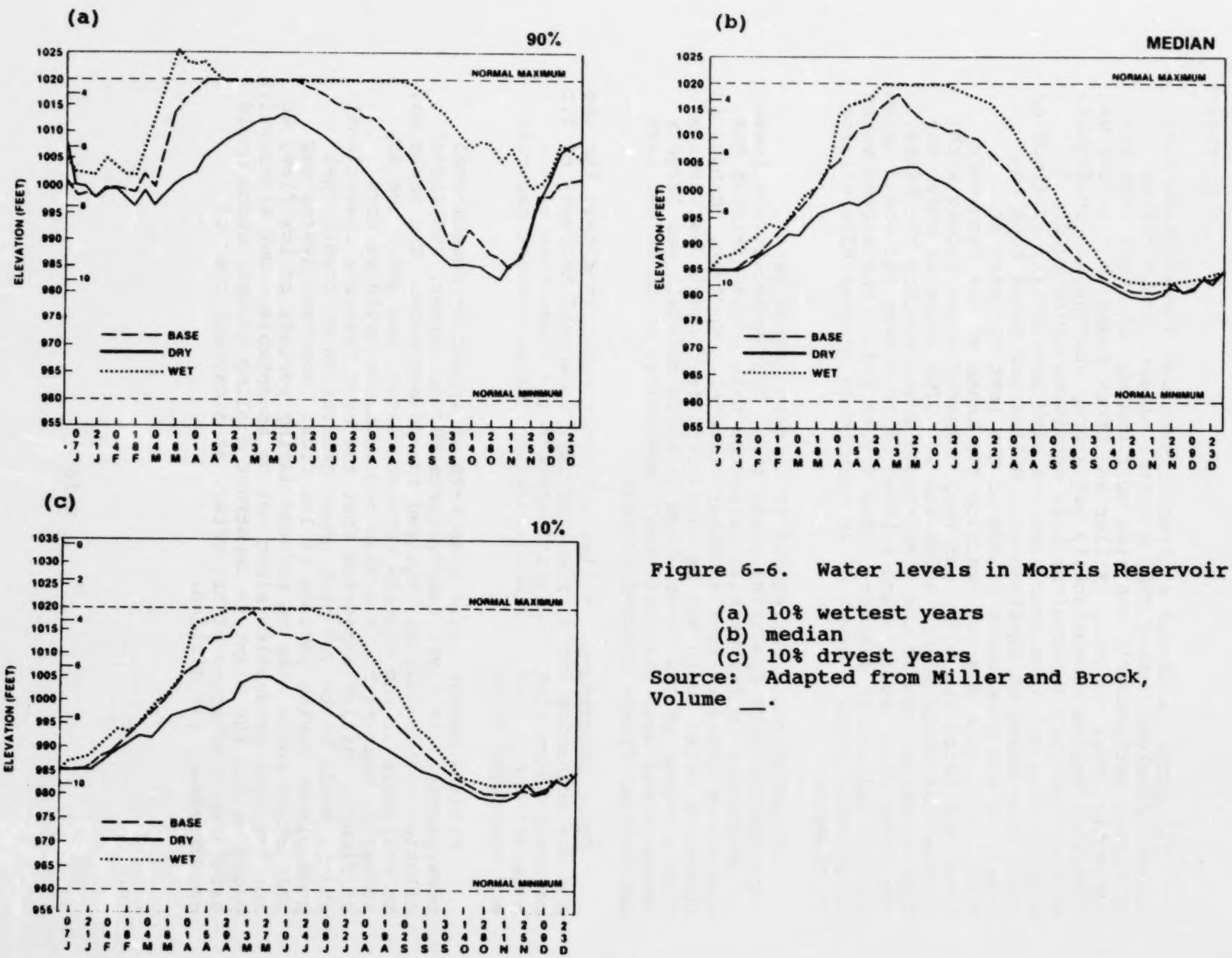

Figure 6-6. Water levels in Morris Reservoir

(a) 10% wettest years
(b) median
(c) 10% dryest years

Source: Adapted from Miller and Brock, Volume __.

Flooding. Although a dryer climate would exacerbate many current problems facing TVA, a wetter climate could create problems, particularly the risk of flooding, in areas that are currently under control. Miller and Brock found that in the wet scenario, during exceptionally wet years, storage was inadequate at the tributary reservoirs; this condition could result in uncontrolled spillage over dams. A high probability of flooding would also exist at Chattanooga. Miller and Brock took the levels of the five worst floods of the last 50 years at Chattanooga that did not overflow the banks of the Tennessee River and flood the city, and they compared these floods with floods that would result under the wet GISS scenario.Under the GISS scenario, two of the five floods would overtop the banks. The worst flood would reach a level of 56.3 feet and would cause over $1 billion in damages. (See Figure 6-7.) The second worst flood would reach a level of 46 feet, causing over $200 million in damages.

Flooding could be reduced if climate change were incorporated into operating rules that, kept water levels lower in reservoirs on tributaries (although this would diminish the hydropower benefits from a wetter climate). However, changes in operating rules would not be sufficient to protect Chattanooga from a repeat of the worst storm in which rainfall was largely concentrated over the "mainstem" reservoirs, which do not have substantial flood- control storage.

Power Generation. Miller and Brock calculated that the wet and dry scenarios imply, respectively, an annual increase of 3.2 megawatt-hours (16%, $54 million/year) and a decrease of 4.6 megawatt-hours (24%, $87 million/year), given current capacity and operating rules.

Climate change could also have an impact on fossil-fuel powerplants. If river temperatures become warmer, additional dilution water would be required for powerplants. The water may be available if the climate becomes wetter, but under the dry scenario, meeting minimum flow requirements would be more difficult. Miller suggested that the most feasible operational change would be to cut back power generation at fossil/fuel powerplants during periods of low flow. However, hydropower production would also be reduced during periods of low flow, so cutting back production might not be acceptable. One alternative would be for the plant to construct cooling towers, which would eliminate discharges of hot water, at a capital cost of approximately $75 million.

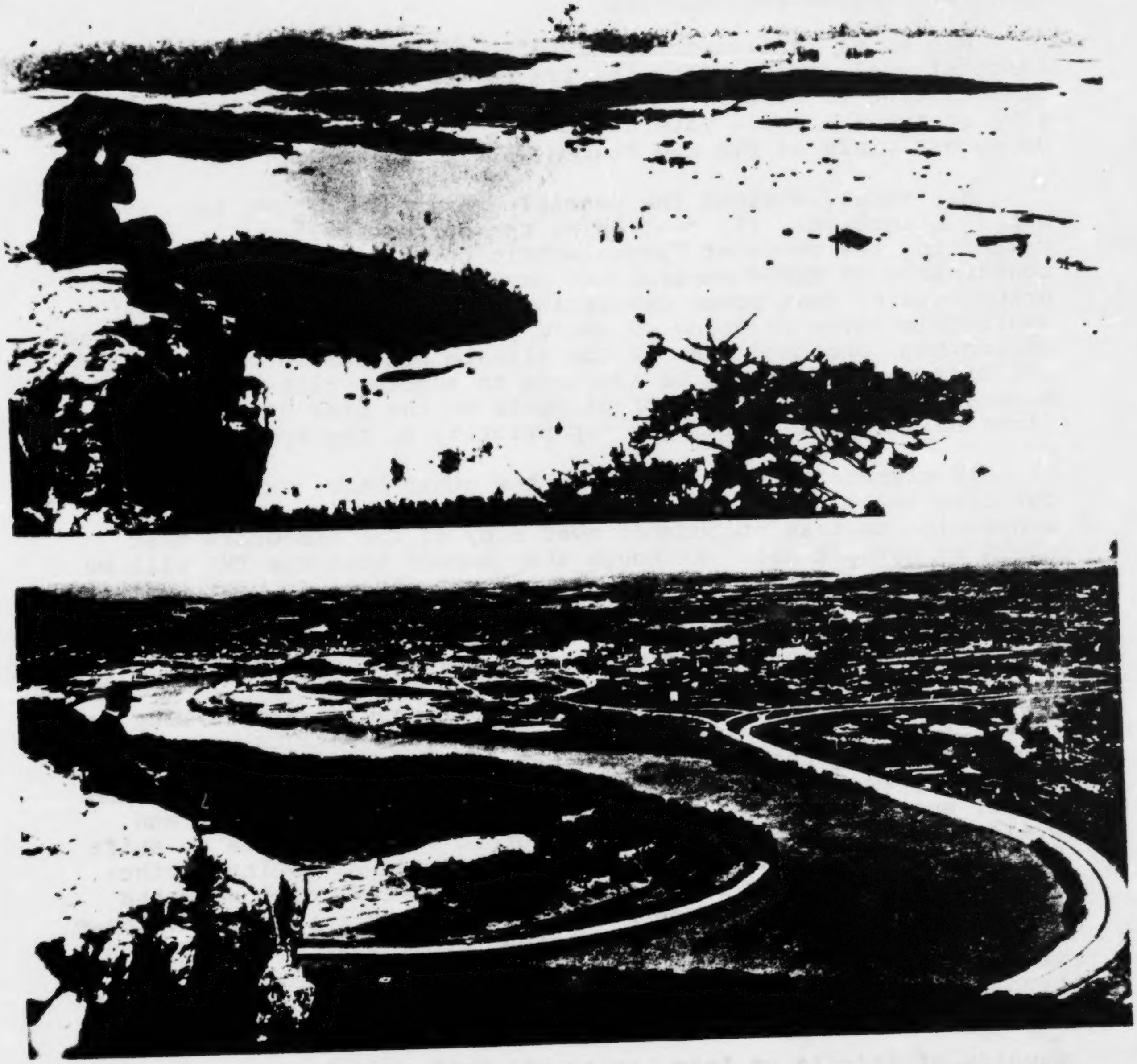

Figure 6-7. Chattanooga was vulnerable to flooding until the TVA system of dams was constructed. The upper photo shows the 1867 Flood, with levels similar to what Miller and Bruck project could happen under the wet scenario.

Source: Tennessee Valley Authority

Tennessee Valley Policy Study

Meo et al. analyzed the history, statutory authority, and institutional structure of the TVA to assess the ability of the organization to respond to climate change. Their analysis relied both on the available literature and on interviews with a few dozen officials of TVA and states within the region.

Meo et al. divided the possible responses of TVA into two broad categories: (1) continuing the current policy of maximizing the value of hydroelectric power, subject to the constraints of flood control and navigation; and (2) modifying priorities so that power generation would be subordinated to other objectives if doing so would yield a greater benefit to the region.Meo concluded that if the climate becomes wetter, current policies would probably be adequate to address climate change because the only adverse effect would be the risk of additional flooding, which is already a top priority of the system.

If climate becomes drier, on the other hand, existing policies might be inadequate, because they require power generation to take precedence over many of the resources that would be hardest hit. Although they expect that the TVA will be more successful at addressing the current (1988) drought, Meo et al. found that during the 1985-86 drought, falling lake levels impaired recreation and reduced hydropower generation, forcing the region to import power while five powerplants sat idle.

Meo et al. point out that groundwater tables are falling in parts of the region, in part because numerous tributaries recharge the aquifers whenever water is flowing but are allowed to run dry when water is not being released for hydropower. Meo et al. suggest that the deteriorating groundwater quality and availability are likely to lead a number of communities to shift to surface water supplies in the coming decades, adding another use that must compete for the water that is left over when the demands for power have been met. Even with current climate these contend, the TVA should assess whether other uses of the region's water resources would benefit the economy more. If climate became drier, the need for such a reevaluation would be even more necessary.

Studies of Effects on Lake Lanier and Apalachicola Bay

Figure 6-8 shows the boundaries of the Chattahoochee-Flint-Apalachicola River Basin, which encompasses 19,800 mi^2. The Corps of Engineers and others who manage the Chattahoochee River as it passes through Lake Lanier on its way to the Apalachicola estuary and the Gulf of Mexico face many of the same issues as those faced by the TVA. However, they also are managing the water supply of Atlanta, the 2nd largest city in the Southeast, and the flow of water into an estuary that supports the most productive fishery in Florida. (Statistical Abstract of U.S.: 1988, Department of Commerce.)

A number of researchers were involved in EPA's assessment of the potential implications of climate change for this watershed. A study of Lake Lanier and a study of the implications for the fish in Apalachicola Bay are discussed in the following sections of this chapter.

Lake Lanier

Lake Lanier, located 30 miles northeast of Atlanta, is a source of water for the city and nearby jurisdictions. Federal statutes require the U.S. Army Corps of Engineers to manage Lake Lanier to provide flood control, navigation, and hydropower. The lake is also managed to mind nonstatutory objections such as recreation, minimum flows for environmental dilution, and water supply.

Since Lake Lanier was dammed in 1957, the statutory objectives of flooding and navigation have been met; historical annual hydropower generation has been 199, 134 MWH[1], equal to 2% of today's power requirements for Atlanta[2]; and the releases of water have fulfilled the additional minimum flow needed to dilute the effluents from sewage treatment plants.

During the last two decades, the lake's shoreline has been substantially developed with marinas, houses, and hotels. To a large degree, the residents have become accustomed to the higher water levels that have prevailed from the 1970s through 1984.

Droughts from 1985 to the present, however, have lowered lake levels, disrupting recreation. In the summer of 1986, navigation for recreational boats located downstream of the lake was curtailed due to minimal releases from the lake. Recently, Atlanta imposed water-use restrictions, with the objective of cutting consumption 10-20%. A bill has been introduced to add recreation to the list of statutory purposes (HR-4257). [Rep. Jenkins, Rep. Barnard, Rep. Darden. HR-4254 "Georgia Reservoir Management Improvement Act of 1988," 100th Congress, 20 Session].

Runoff in the Chattahoochee River Basin

To assess the potential implications of climate change for Lake Lanier, Haines estimated the flows of water into the lake.

Study Design. Haines calibrated the Sacramento hydrology model developed by the National Weather Service (Burnash, 1973) to the conditions found in the watershed of the upper Chattahoochee River. He then generated scenarios of riverflow for the baseline climate and the three doubled CO_2 scenarios.

Limitations. The Sacramento model was designed primarily for flood forecasting, not base flow. In addition, the model was calibrated using the data on evaporation of water from pans, which is not perfectly correlated with evapotranspiration.

Results. As with the Tennessee River, the major climate models disagree on whether the Chattahoochee watershed would become wetter or dryer with an effective doubling of greenhouse gases. Haines estimated that the wetter GISS model would increase the average annual riverflow of the Chattahoochee River by 13%, while the drier OSU and GFDL models imply declines of 19 and 27%, respectively, as shown in Figure 6-9. The GISS scenario implies slight decreases in winter flow and increases the rest of the year. The GFDL scenario shows substantial decreases throughout the year, with almost no flow in late summer. The OSU scenario also shows reductions, but the reduction is greatest during the flood season (February to May) and negligible during the dry season (late summer/early fall).

Management of Lake Lanier

Sheer used the calculation of riverflow from Haines to estimate the management implications of climate change.

Study Design. Sheer modified a monthly water balance model/operations model previously applied in Southern California for the lake, based on current operating rules for the reservoir. For the first set of runs, the model assumes that (1) minimum flows are maintained for navigation and environmental dilution at all times, (2) lake levels are kept low enough to prevent flooding, (3) historic rates of consumption continue, and (4) peak hydropower generation is maximized. To ensure that the assumptions adequately reflect the actual decision rules used by water managers, Sheer reviewed the rules with local officials from the Corps of Engineers, the Atlanta Regional Council, and others responsible for managing the water supply. In a second set of runs, Sheer examined the impacts of climate change under alternative operating rules that assume recreation is also a statutory objective.

Limitations. The Sheer model does not consider changes in demand for water due to climate change. In addition, model results were not compared to actual historic lake levels.

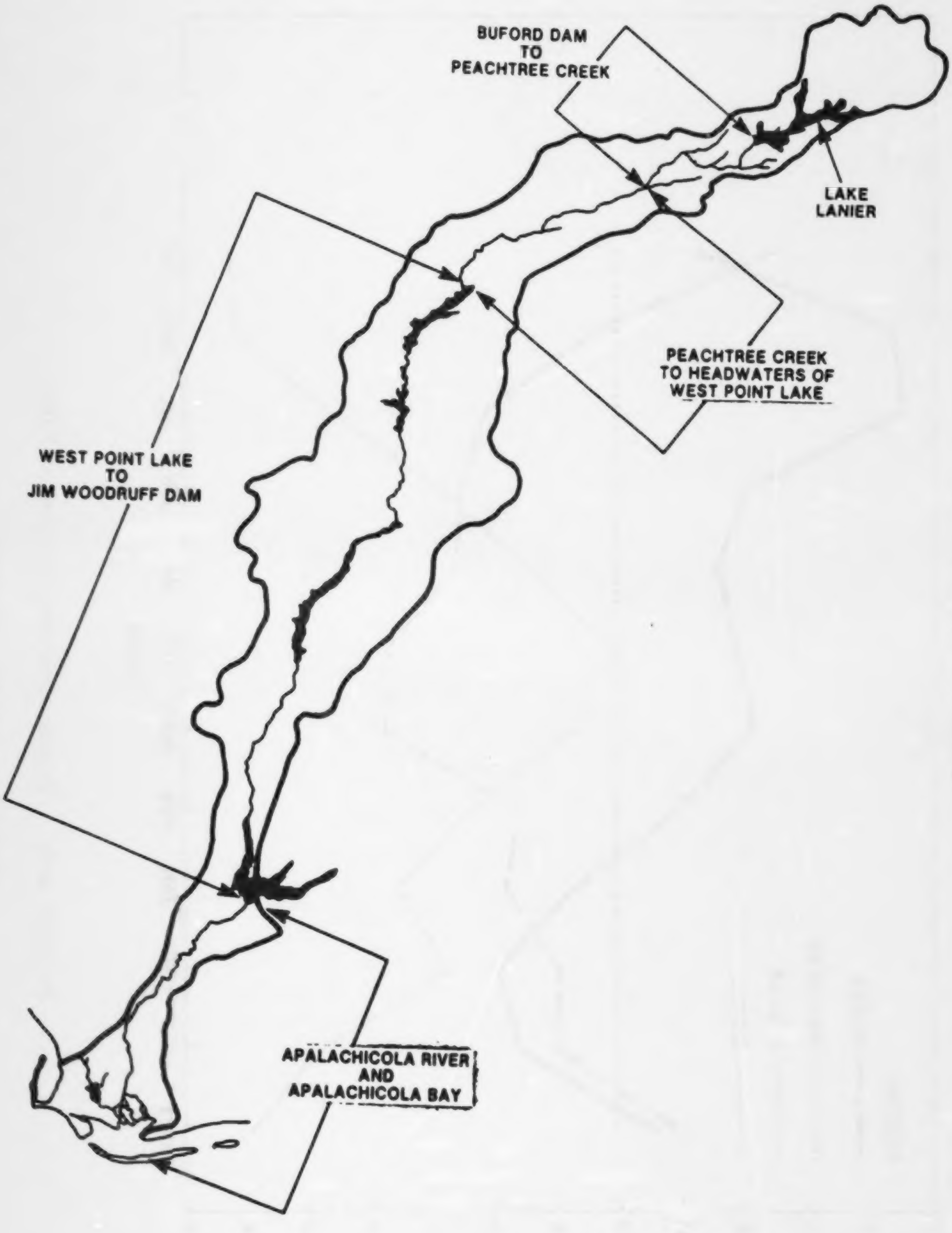
BUFORD DAM
TO
PEACHTREE CREEK
LAKE
LANIER
PEACHTREE CREEK
TO HEADWATERS OF
WEST POINT LAKE
WEST POINT LAKE
TO
JIM WOODRUFF DAM
APALACHICOLA RIVER
AND
APALACHICOLA BAY

Figure 6-8. Drainage area of the Apalachicola-Chattahoochee-Flint River system.

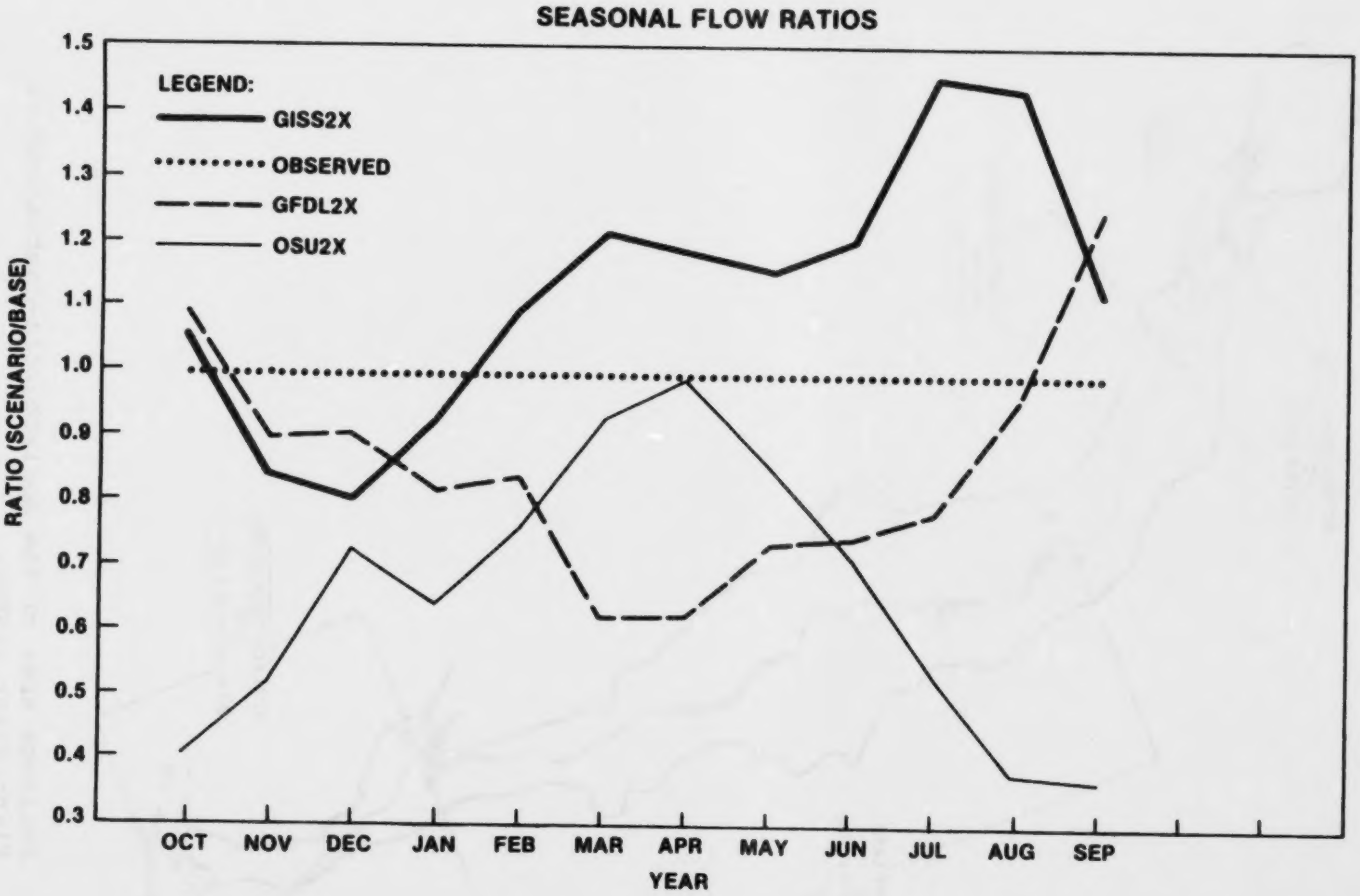

Figure 6-9. Upper Chattahoochee - $2XCO_2$

Source: Hains, Volume _.

Results. Figures 6-10 shows Sheer's estimates of lake levels. Figure 6-11 shows quarterly hydropower production. Under the wet GISS scenario, annual power production would increase by 9%. The higher streamflows in this scenario would still be well below those that occasionally occurred before Lake Lanier was closed; hence, no significant threat of flooding would exist for a repeat of the climate of 1951-80. Under the dry GFDL scenario, however, power production would drop 47%, and lake levels would be likely to drop enough to substantially disrupt recreation. This scenario assumes that Atlanta would continue to take as much water as it does currently (a conservative assumption given the area's rapid growth).

Sheer also examined the implications of making recreation a statutory objective. Although, it would be possible to maintain lake levels, even in the dry GFDL scenario. Altanta's water supply would be threatened. With the current climate, strict enforcement of such a policy would result in Lake Lanker. Although the wet GISS scenario would reduce this to 1 month every30 years, under the dry GFDL scenario, Atlanta would have to use an alternative source of water one to three months each summer.

Implications. Climate change combined with population growth may require water managers to reexamine the tradeoffs between the various uses of the Chattahoochee River and Lake Lanier. A number of local water officials who met with Sheer suggested that an appropriate response to changing water availability might be to relax minimum flow requirements for navigation and environmental quality. They reasoned that minimum flows for environmental purposes are based on conditions that prevail only when sewage treatment plants are at their maximum discharge and temperatures are high, and that little is accomplished by maintaining minimum flows for navigation because ship traffic is light in the lower Chattahoochee. Others argued, however, that it would be unwise to assume that minimum flows could be decreased because future growth may increase the need for dilution of effluents, and warmer temperatures would speed biological activity. The likely impacts of climate change on Apalachicola Bay may also increase the need to maintain minimum flows.

Apalachicola Bay, Florida

Apalachicola Bay supports hundreds of commercial fishermen; over 80% of Franklin County earns a livelihood from the bay (Meo, Vol. _). The contribution of fishing to the area was estimated at $20 million for 1980, representing 90% of Florida's oyster harvest and 10% of its shrimp harvest. This figure is projected to grow to $30-60 million by 2000.

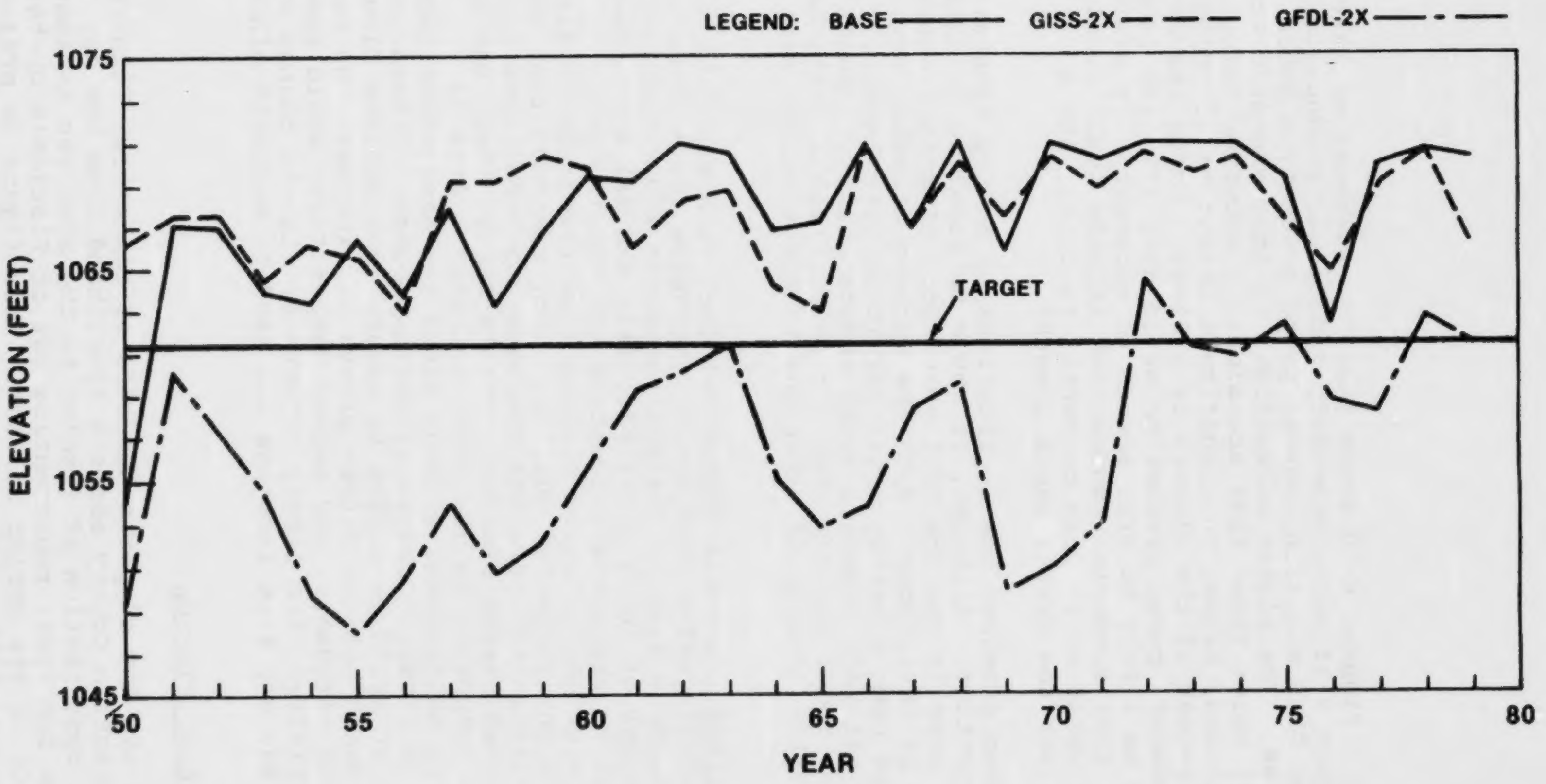

Figure 6-10. Lake Lanier elevation (September).

Source: Sheer and Randall, Volume __.

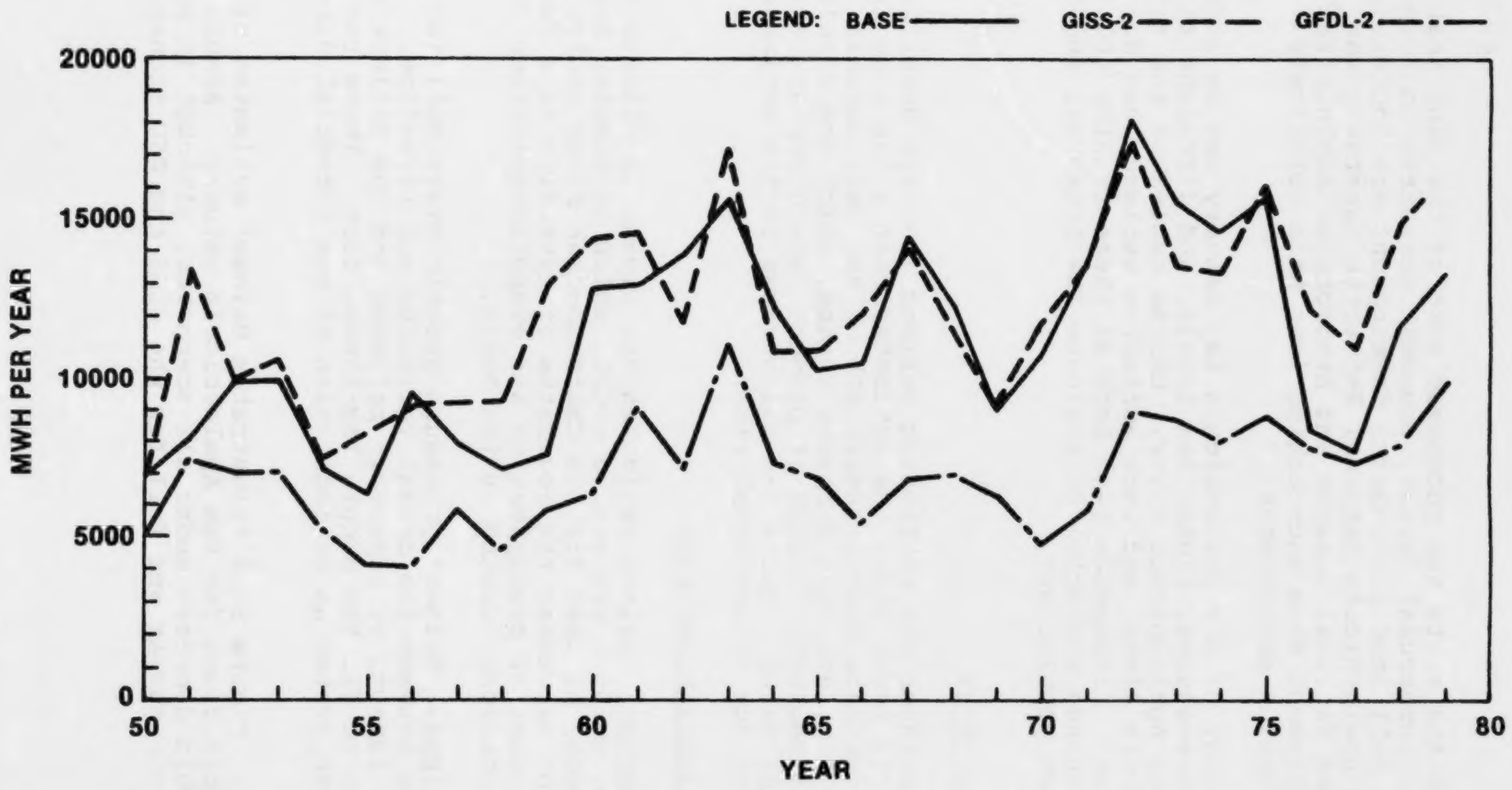

Figure 6-11. Lake Lanier power generation.

Source: Sheer and Randall, Volume __.

Although the state has purchased most of the land that is not part of a commercial forest, economic pressures on forestry companies to sell land for coastal development are increasing. In 1979, the Apalachicola National Estuarine Sanctuary was created by the National Oceanic and Atmospheric Administration to prevent development from encroaching into this relatively pristine estuarine environment.

The biology of the Apalachicola Bay estuary may be affected by higher temperatures, higher sea levels, and different flows of water into the Apalachicola River. Haines estimated the flow of the Apalachicola River, and Park estimated wetland loss due to sea level rise. Livingston used both of these results and the temperature change scenarios to evaluate the potential impacts on the bay's fish populations.

Sea Level Rise

Park's methods for estimating wetland loss are described in chapter 9: Sea Level Rise. He estimated that a 1-m rise in sea level would inundate approximately 60% of the salt marshes in Apalachicola Bay, and that mangrove swamps, which are rarely found outside southern Florida at present, would replace the remaining salt marsh. Table 6-6 illustrates Park's estimates of wetland shifts due to sea level rise.

Apalachicola River Flow

Study Design. Haines estimated the impact of climate change on riverflow, using a regression model, which is simpler than the Sacramento model he used for the Chattahoochee River analysis. The regression expressed the logarithm of riverflow as a function of the logarithms of precipitation and evapotranspiration for a few weather stations located in the basin.

Limitations. Haines' procedure greatly oversimplified the relationships between the causal variables and riverflow, ignoring the impacts of reservoir releases and the failure of the relationships to fit the simple log-linear form. These results should be interpreted as an indication of the potential direction of change.

Results. Figure 6-12 illustrates Haines' estimates of average monthly flows for the Apalachicola estuary. Annual riverflow would decrease under all scenarios, although it would increase in the summer and fall for the GISS and OSU scenarios, respectively.

Table 6-6. Loss of Coastal Wetlands in Apalochicola Bay (hectares)

	1987	Baseline	50	100	200
Swamps	9.46	6.71	6.26	5.47	4.16
Fresh Marsh	1.46	1.27	1.17	1.00	0.25
High Marsh	1.19	0.37	0.035	0.035	0.020
Low Marsh	3.42	2.33	0.388	0.062	0.032
Mangrove Wetlands	0	0	3.057	2.13	1.80

Source: Park

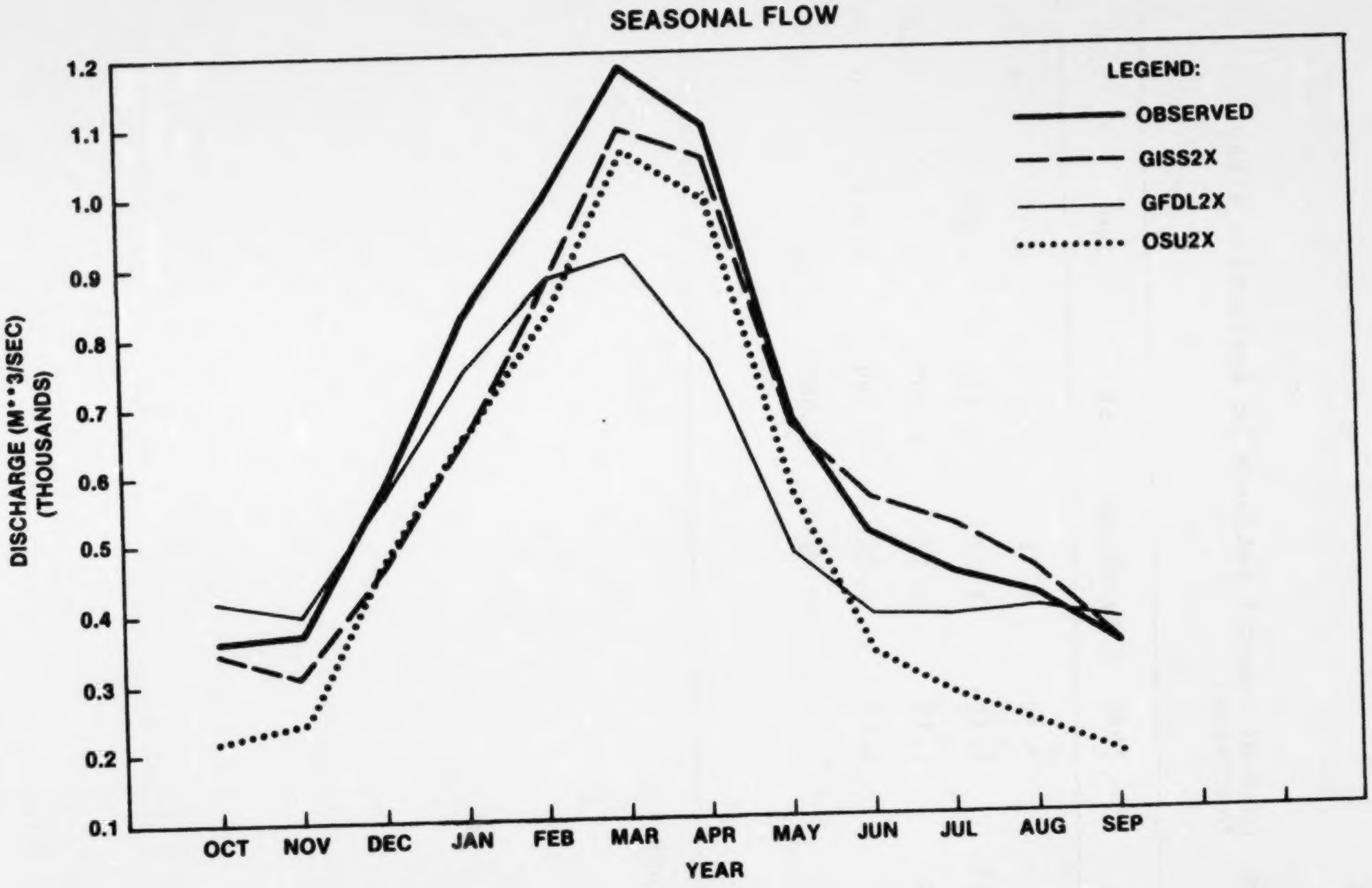

Figure 6-12. $2XCO_2$ Flow into Apalachicola Bay

Source: Hains, Volume __.

Fish Populations in Apalachicola Bay

Study Design. Using data from the literature on the tolerance of various species to warmer temperatures, Livingston estimated the number of months in a typical 30-year period during which the estuary would be too hot for these species and extrapolated this information to estimate reductions in populations.

Hydrologic modeling was not used to estimate the combined impacts of sea level rise and changing riverflow on salinity. Since Haines estimated that riverflow would be lower under all three scenarios, salinity in Apalachicola Bay would increase. Recent droughts have decreased riverflow by approximately the same magnitude as would be suggested by the dry OSU and GFDL scenarios. Livingston used historic data to estimate regression equations relating riverflow to salinity and salinity to populations of some commercially important seafood species.

Limitations. There is no historical record by which to estimate the impact of warmer temperatures on the Apalachicola (or any other) estuary. Livingston did not model the relationships between various aquatic species or how they would change. He did not consider how finfish and shellfish might adapt to climate change, and he was unable to estimate the impact of wetland loss on populations of finfish and shellfish.

The limitations in Haines' estimates of riverflow do not significantly affect the results of Livingston's study because riverflow was one of several variables to be considered. The uncertainties surrounding changes in rainfall probably dwarf any errors due to Haines' simplified hydrology, and higher temperatures and sea level rise appeared to be more important.

Results. The results of this study suggest a dramatic transformation of the estuary from subtropical to tropical conditions.

Warmer temperatures. Livingston concluded that warmer temperatures would have a profound effect on seafood species in the estuary because they cannot tolerate temperatures much above those that currently prevail. Figure 6-15 compares the number of months in a six-year period (based on 1971-76) in which temperatures exceed a particular level for the current climate and the GISS, GFDL, and OSU scenarios, with known thresholds for major commercial species.

Livingston concluded that crabs, shrimp, oysters, and flounder could not survive in the estuary with the warming projected by the GISS and GFDL scenarios, which imply close to 100% mortality for blue crab larvae and juveniles. The GFDL scenario would also imply over 90% mortality for spotted sea trout, oyster larvae, panfish, and flounder. The mortality under the milder GISS scenario would be only 60%.

Although Livingston concludes that the oysters would probably be eliminated, he cautions that shrimp and other mobile species might adapt by fleeing the estuary for cooler gulf waters during the summer. However, such a flight would leave them vulnerable to predators.

Increased Salinity. Although it appears that sea level rise and warmer temperatures are likely to substantially reduce the productivity of the estuary, the probable impact of precipitation changes is less clear. However, lower flow in the Chattahoochee would combine with sea level rise to increase salinity concentrations in the estuary. Livingston concluded that oysters appear to be the most vulnerable to increases in salinity because oyster drill and other predators, as well as the disease MSX, generally require high salinities. Livingston estimated losses of 10 to 35% for oysters, blue crabs, finfish, and white shrimp under the GFDL scenario due to salinity increases alone.

Sea Level Rise. Livingston also concludes that the loss of wetland acreage would have important impacts on the estuary. Table 6-7 also includes Livingston's estimates of losses in particulate organic carbon, the basic source of food for fish in the estuary. Sea level rise between 50 and 200 cm would reduce available food by 42 to 78%. A proportionate loss in seafood populations would not necessarily occur, since organic carbon food supplies are not currently the constraining factor for estuarine populations. However, wetlands also are important to larvae and small shrimp, crabs, and other species, serving as a refuge from predators. A rise in sea level of a meter or more could lead to a major loss of fisheries.

Despite the adverse impacts on shellfish and flounder, a number of species might benefit from global warming. For example, Livingston concludes that pink shrimp could become more prevalent. Moreover, some finfish spend their winters in Apalachicola Bay and occasionally find the estuary too cold. Other species, such as rock lobster, that generally find the waters too cold at present also may be found in the estuary in the future.

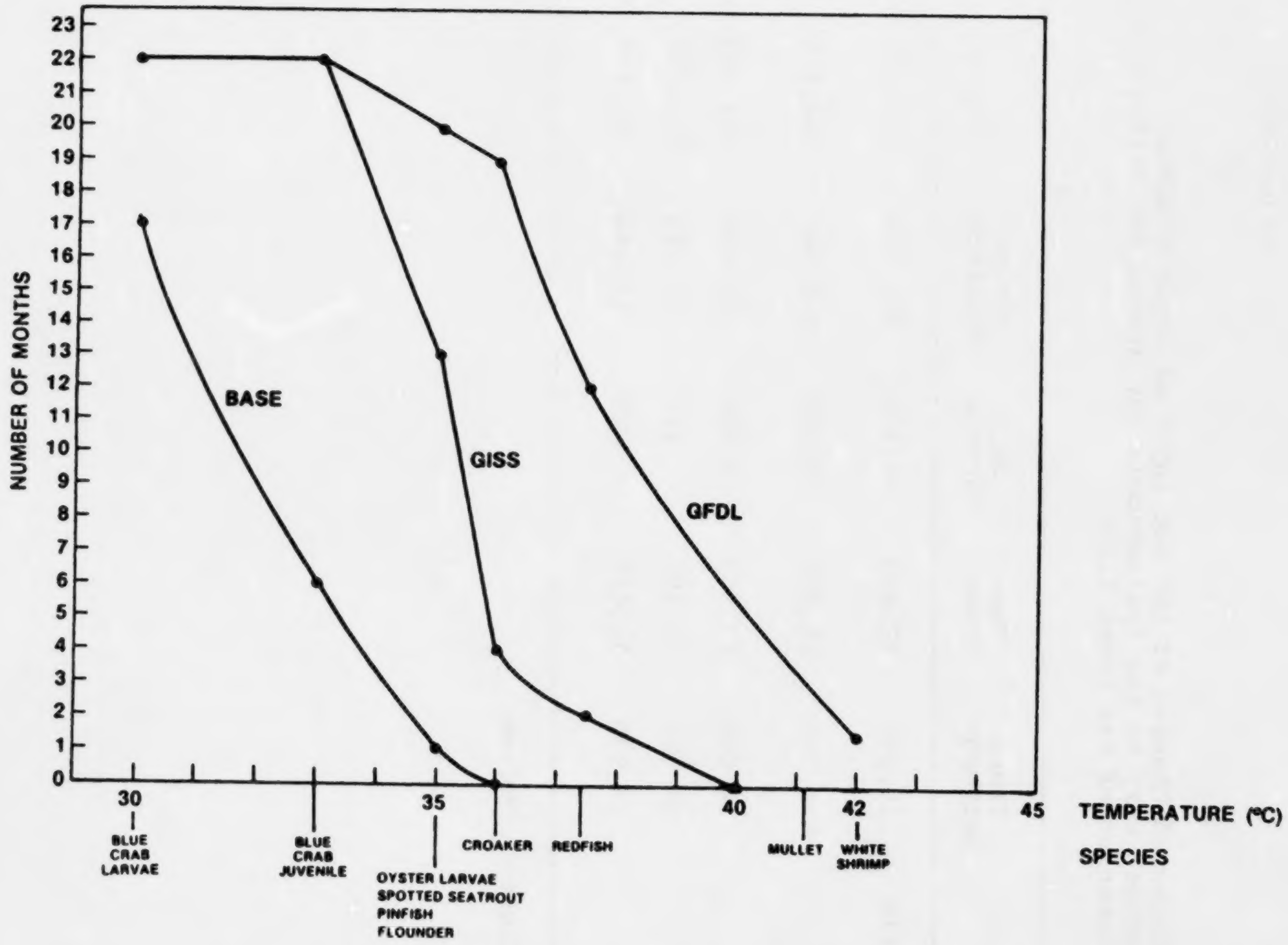

Figure 6-15. Months in a six-year period during which temperatures would be too high for selected species.

Source: Adapted from Livingston, Volume _.

Table 6-7. Projected Changes of the Net Input of Organic Carbon (mtons/year) to the Apalachicola Bay System for Various Scenarios of Sea Level Rise

Factor	Fresh Wetlands	Sea-Grass	Salt Marshes	Phyto-Plankton	Total
Current Scenario for 2100	30,000	27,200	46,905	233,280	337,385
Baseline Sea Level Rise	26,100	28,700	23,500	144,640	222,940
0.5 M Rise	24,000	28,800	4,690	71,450	128,940
1.0 M Rise	21,300	30,100	940	58,790	111,130
2.0 M Rise	4,980	31,035	780	15,160	51,955

Source: Livingston, Volume __.

Implications. Based on Livingston's projections, Meo et al. (Volume __) used current retail prices of fish to estimate that the annual net economic loss to Franklin County would be \$5-15 million under the GFDL scenario, \$1-4 million under GISS, and \$4-12 million under the OSU scenario.

Livingston's results should not be interpreted to mean that fishing will be eliminated from Apalachicola Bay. The extent to which commercially viable tropical species could replace the species that are lost simply cannot be estimated at this time.

Agriculture

Agriculture in the Southeast will be directly affected by changes in climate and indirectly affected by changes in economic conditions and pests. This section presents results from a crop modeling study of yield changes by Peart et al., and regional results from national studies of agricultural production shifts by Adams et al. and of impacts of changes in pest populations by Stinner et al.

Crop Modeling Study

Study Design

Peart et al. used the crop models CERES-Maize (Jones and Kiniry, 1986) and SOYGRO (Wilkerson et al., 1985) to estimate the impacts of climate change on yields of corn and soybeans for 19 sites throughout the Southeast and adjacent states. These models have been used for several years by agricultural scientists to project the impacts of short-term climatic variations. They incorporate the responses of crops to solar radiation, temperature, precipitation, and soil type, and they have been validated over a large range of climate and soil conditions in the United States and other countries.

The major variable not considered by these and other existing agricultural models is the direct "fertilization effect" of increased levels of atmospheric carbon dioxide. Peart et al., therefore, modified their models to consider both the increased rate of photosynthesis and the increased water-use efficiency that corn and soybeans have exhibited in field experiments.

Limitations

The analysis of combined effects is new research and will need further development and refinement. The model runs use simple parameters for CO_2 effects, assume higher atmospheric concentration CO_2

than are predicted, and may be overestimates of crop yields (see Chapter 10 of this report).

The scenarios examining the effects of climate alone on crops assumed that soils were relatively favorable for crops, with low salinity or compaction, and assumed no limits on the supply of all nutrients, except nitrogen. In addition, the analysis assumes no technological adjustments are made by farmers to improve crop yields. Possible negative impacts due to changes in storm frequency, droughts, and pests and pathogens are not factored into this study.

Results

Soybean Yields. Table 6-8 illustrates the results of the soybean model for 13 nonirrigated sites in the study area, as well as Lynchburg, Virginia, a colder site included for comparison purposes.

The results differ between the wet GISS and dry GFDL scenarios. In the GISS scenario, the cooler sites in Georgia and the Carolinas mostly show declines in soybeans yields of 3 to 25%, and the other sites show declines of 20 to 40%, ignoring CO_2 fertilization. When the latter effect is included, the Atlantic states experience gains of 11 to 39%, and the other states vary from a 13% drop in Memphis to a 15% gain in Tallahassee. (Tennessee fares worse than the North Carolina sites at similar latitudes because its grid cell does not receive as favorable an increase in water availability.)

By contrast, the dry GFDL scenario results in very large drops in soybean productivity, with all but one site experiencing declines greater than 50% and eight sites losing over 75%, considering only the impact of climate change. Even when CO_2 fertilization is considered, all but four sites experience losses greater than 50%.

Corn Yields. Table 6-9 shows that the two scenarios differ in a similar fashion for nonirrigated corn. However, in the case of irrigated corn, where the analysis primarily reflects the impact of temperature increases, the two scenarios show more agreement. Ignoring CO_2 fertilization, the GISS model shows drops of 13 to 20%, and GFDL shows drops of 20 to 35%. When CO_2 fertilization is included, the GISS scenario implies declines of less than 8% for all sites, and the GFDL model shows similar declines for two sites and respective declines of 17 and 27% for Charlotte, North Carolina, and Macon, Georgia.

Irrigation. The two scenarios show more agreement for agricultural fields that are already irrigated. Since the changes in water availability are irrelevant here, the impacts are dominated by the increased frequency of very hot days.

The results are mixed on whether currently dry land areas would be shifted to irrigation. Table 6-10 shows the percentage increases in

Table 6-8. Impacts of $2xCO_2$ Climate Change on Soybean Yields for Selected Southeastern Sites (yield as a percentage of current yield)

State	Climate Change and CO_2 Fertilization		Climate Change Only	
	GISS	GFDL	GISS	GFDL
Memphis, TN	87	30	62	18
Nashville, TN	104	79	70	48
Charlotte, NC	132	12	93	8
Raleigh, NC	139	24	97	13
Columbia, SC	118	38	80	22
Wilmington, NC	125	59	89	38
Atlanta, GA	127	33	89	22
Macon, GA	111	18	75	9
Tallahassee, FL	115	83	80	49
Birmingham, AL	100	71	69	46
Mobile, AL	92	error	66	57
Montgomery, AL	90	32	61	16
Meridian, MS	91	36	63	22
Lynchburg, VA[a]	146	45	101	26

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[a] Peart et al. investigate a number of sites in states adjacent to the Southeast. Lynchburg is included to permit comparison of Southeast results with a colder site.

Source: Peart et al, Volume __.

Table 6-9. Impacts of $2xCO_2$ Climate Change on Corn Yields

Scenario	Charlotte, NC	Macon, GA	Meridian, MS	Memphis, TN
Climate Change Only				
Irrigated				
GISS	87	81	80	82
GFDL	71	65	80	80
Rainfed				
GISS	100	98	84	93
GFDL	24	18	30	37
Climate Change and CO2 Fertilization				
Irrigated				
GISS	101	92	93	95
GFDL	83	73	93	94
Rainfed				
GISS	116	114	98	113
GFDL	28	20	36	37
CO_2 Fertilization Only				
Irrigated	117	113	117	118
Rainfed	116	116	116	116

Source: Peart et al, Volume __.

Table 6-10. Increases in Corn Yields from a Shift to Irrigation (percent, assuming no CO_2 fertilization)

State	No Climate Change	GISS	GFDL
Memphis, TN	70	50	370
Nashville, TN	65	49	205
Charlotte, NC	64	43	486
Raleigh, NC	51	28	444
Columbia, SC	58	47	386
Wilmington, NC	16	8	50
Atlanta, GA	15	7	79
Macon, GA	61	33	589
Birmingham, AL	6	9	61
Mobile, AL	36	41	91
Montgomery, AL	72	39	593
Meridian, MS	62	53	423
Lynchburg, VA*	56	37	361

Source: Derived from Tables 6-8 and 6-9 (see text) yields that would result from adding irrigation for no climate change and the two climate change scenarios. All but four sites could increase yields today by 50-75% by irrigating. Under the wetter GISS scenario, irrigation only would increase yields 25-50%. However, under the dry GFDL scenario, irrigation would increase yields by 200-600% -- that is, it would mean the difference between crop failure and a harvest slightly above today's levels in most years. Even without CO_2 fertilization, 75% of the nonirrigated southeastern sites could gain more from irrigation than they would lose from the change in climate resulting from the GFDL scenario.

A farmer's decision to irrigate, shift to other crops, or remove land from production would depend to a large degree on what happens to future prices of both crops and water. Even though water is plentiful today, the capital costs of irrigation prevent most farmers in the Southeast from taking advantage of the potential 50% increases in yields. But if crop failures due to drought became as commonplace as Peart et al. project for the dry GFDL scenario, a major increase in irrigation probably would be inevitable.

Shifts in Production

Adams et al. (Volume __) examined the impacts of changes in crop yields on farm profitability and cultivated acreage in various regions of the United States. (The methods for this study are discussed in Chapter 10: Agriculture) Their results suggest that the impact of climate change on southeastern agriculture would not be directly proportional to the impact on crop yields (Table 6-11).

Considering only the impact of climate change, Adams et al. found that the GISS and GFDL scenarios would reduce crop acreage by 10 and 16%, respectively. This is a small difference, given Peart's projection that all but one site would lose more than half of their production under the GFDL scenario, while none of the sites would lose that much under the GISS scenario. When CO_2 fertilization is considered, however, Adams et al. project respective declines in farm acreage of 57 and 33% for the GISS and GFDL scenarios.

The conclusion that the greatest decline in farming could occur under the scenario in which yields increase is not unreasonable in light of the substantial decline in farming that took place during the period of rapid technical innovation after World War II. As yields increase, prices decline. Adams et al. project that most areas of the nation would lose farm acreage. However, Adams et al. estimate that the Southeast would experience the worst losses: while the Southeast has only 13% of

Table 6-11. Impact of Climate Change on Cultivated Land in the Southeast

Region	Baseline	With Direct CO_2 GISS	With Direct CO_2 GFDL	Without Direct CO_2 GISS	Without Direct CO_2 GFDL
Acreage (millions)					
SE coast	12.5	8.7	7.8	11.5	11.2
Appalachia	15.5	2.8	7.4	14.1	12.9
Delta	19.9	9.3	16.7	17.7	16.2
Total	47.9	20.8	31.9	43.3	40.3
Percent loss					
SE coast		30	38	8	10
Appalachia		82	52	9	17
Delta		53	16	11	19
Total		57	33	10	16

Note: SE coast includes Florida, South Carolina, Georgia, Alabama.
Appalachia includes North Carolina, Tennessee, Virginia, West Virginia, Kentucky.
Delta includes Mississippi, Louisiana, Arkansas.

Source: Adams et al, Volume __.

the cultivated acreage, it would account for 60-70% of the nationwide decline in farm acreage.

When the CO_2 fertilization effect is ignored, the reductions in acreage would be much smaller, although the Southeast would still account for 40-75%. The general decline in yields would boost prices, which would make it economical for many farmers to irrigate and thereby avoid the large losses associated with a warmer and possibly dryer climate.

Agricultural Pests

The modeling and economic studies of agriculture do not consider the impact of pests on crop yields. However, Stinner et al. (Volume ___) suggest that global warming would increase the range of several agricultural pests that plague southeastern agriculture. (See Chapter 10: Agriculture for details on the methods of this nationwide study.)

Stinner et al. point out that the northern ranges of potato leafhoppers, sunflower moths, black cutworms, and several other southeastern pests are limited by their inability to survive a cold winter. Thus, milder winters would enable them to move farther north, as illustrated in Figure 6-16. Stinner also points out that more droughts could also increase the frequency of pest infestations.

Implication of Agriculture Studies

Agriculture appears to be at least as vulnerable to a potential change in climate in the Southeast as in any other section of the country. Unlike many of the colder regions, the benefits of a longer growing season would not appreciably offset the adverse impacts of warmer temperatures in the Southeast, where cold weather generally is not a major constraint to. agricultural production.

Florida may present an important exception to the generally unfavorable implications of climate change for crop yields. Although Florida is the warmest state in the Southeast, its agriculture appears to be harmed by cold temperatures more than the agriculture of other states in the region. In recent years, hard freezes have destroyed a large fraction of the citrus harvest several times. As a result, the industry is moving south into areas near the Everglades, and sugarcane, which also thrives in warm temperatures, is expanding into the Everglades themselves. Global warming could enable the citrus and sugarcane areas to include most of the state. Warmer temperatures also would help coffee and other tropical crops that are beginning to gain a foothold in the state.

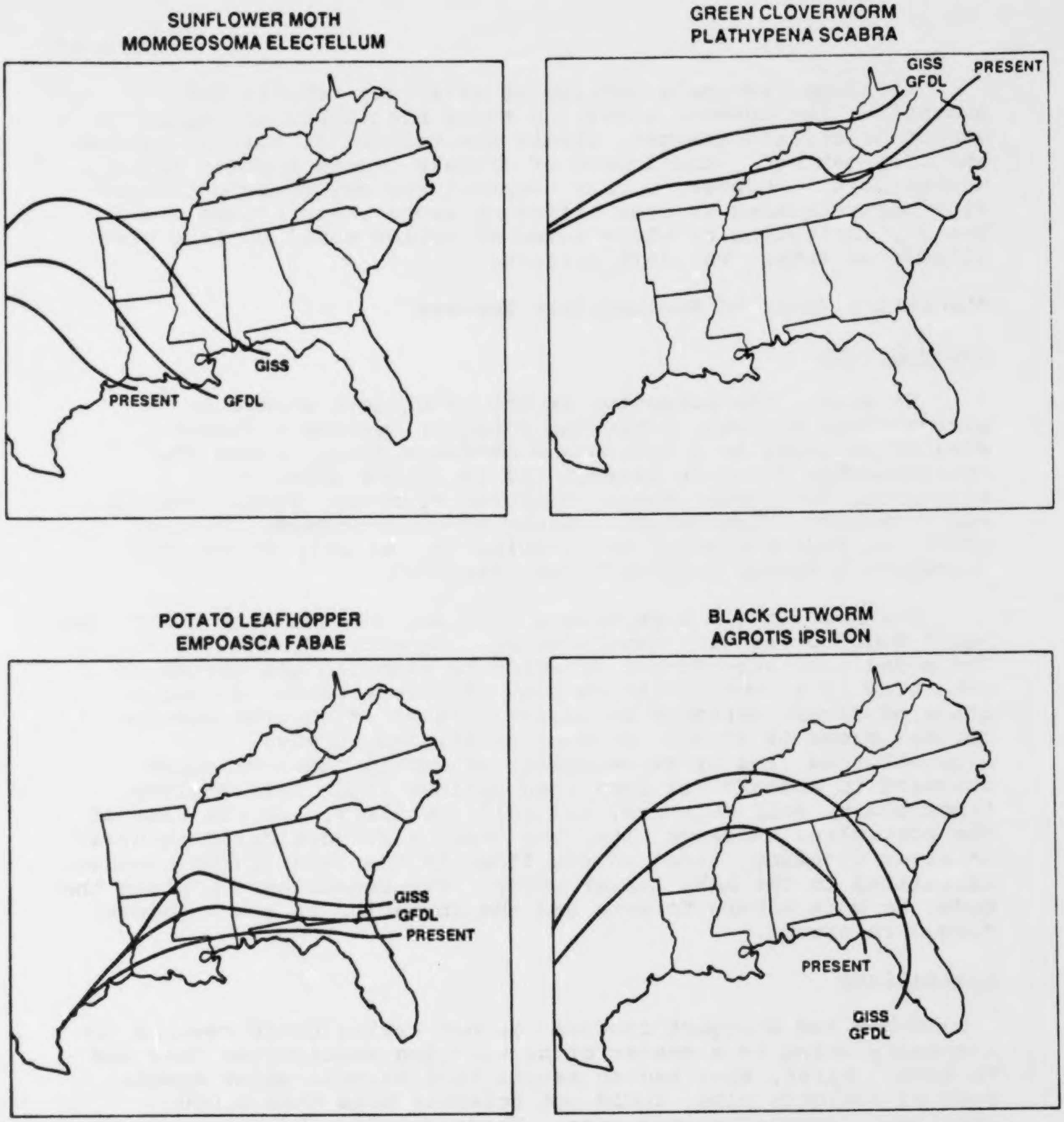

SUNFLOWER MOTH
MOMOEOSOMA ELECTELLUM
GISS
PRESENT
GFDL
GREEN CLOVERWORM
PLATHYPENA SCABRA
GISS
GFDL
PRESENT
POTATO LEAFHOPPER
EMPOASCA FABAE
GISS
GFDL
PRESENT
BLACK CUTWORM
AGROTIS IPSILON
PRESENT
GISS
GFDL

Figure 6-16. Present and predicted northern ranges of various agricultural pests.

Source: Stinner et al, Volume __.

Although Florida's surplus of water may make it the exception, the current situation there highlights an important aspect of climate change: Within the context of current prices and crop patterns, the impact of climate change appears to be unfavorable. However, warmer temperatures may present farmers with opportunities to grow different crops whose prices would justify irrigation or whose seasonal cycles would conform more closely to future rainfall patterns.

Simulation Study of Southeastern Forests

Study Design

To assess the potential impact of climate change on southeastern forests, Urban and Shuggart applied a forest simulation model to a bottomland hardwood forest along the Chattahoochee River in Georgia and to upland sites near Knoxville, Tennessee; Macon, Georgia; Florence, South Carolina; and Vicksburg, Mississippi. Their study considered the OSU, GFDL, and GISS scenarios for doubled CO_2, as well as the GISS transient A scenario through the year 2060.

The model these researchers used was derived from FORET, the "gap" model originally developed by Shuggart and West (1977). The model simulates forest dynamics by modeling the growth of each tree in a representative plot of forest land. It keeps track of forest dynamics by assigning each of 45 tree species optimal rates of growth, seeding rates, and survival probabilities, and by subsequently adjusting these measures downward to account for less than optimal light availability, temperature, soil moisture, and soil fertility. In the case of the bottomland hardwood site, the model also considered changes in river flooding, based on the flows in the lower Chattahoochee calculated in the Lake Lanier study. The researchers applied the model to both mature forests and the formation of a new forest from bare ground.

Limitations

Urban and Shuggart caution against taking their results too literally owing to a number of simplifying assumptions they had to make. First, they had to assume that certain major species, such as loblolly pine, could not tolerate more than 6,000 (cooling) degree-days per year. These species are not currently found in warmer areas, but the southern limits of their range are also limited by factors other than temperature: the Gulf of Mexico and the dry climate of Texas and Mexico. Although the 6,000 degree-day line coincides with their southern boundary across Florida, the peculiar environmental conditions of that state make it impossible to confidently attribute an estimate of thermal tolerance to that observation alone. Fortunately, this caveat does not apply to most of the oaks, hickories, and other species found in the cooler areas of the Southeast.

Another important caveat is that the model does not consider the potentially beneficial impact of CO_2 fertilization on photosynthesis, changes in water-use efficiency, or leaf area.

Results

The simulations by Urban and Shugart call into question the ability of southeastern forests to be generated from bare ground, particularly if the climate becomes drier as well as warmer. For the Knoxville site, the dry GFDL scenario implies that a forest could not be started from bare ground, while the GISS and OSU $2xCO_2$ scenarios imply reductions in biomass of 10-25%. For the South Carolina site, only the GISS climate would support a forest, albeit at less than 50% of today's productivity. The Georgia and Mississippi sites could not generate a forest from bare ground for any of the scenarios.

The transient analyses suggest that mature forests could also be lost -- not merely converted to a different type -- if climate changes. Figure 6-17 shows that none of the forests would decline significantly before the year 2030; however, all would decline substantially before 2060. The Mississippi forest would mostly die by 2040, and the South Carolina and Georgia sites by 2060. Only the relatively cool Tennessee site would remain somewhat healthy, although biomass would decline 35%.

Although the simulation results suggest that southeastern forests are unlikely to benefit from the global warming, the impact on forests may not be as bad as the model suggests. Nevertheless, major shifts in forest types are almost certain to occur from the warmer temperatures alone.

Electric Utilities

Linder (Volume __) examined the impact of global warming on the demand for electricity throughout the Southeast for the two GISS transient scenarios. (See Chapter 16: Electricity Demand for additional details on the methods and limitations of this study.) Because Linder's study was limited to electricity, it did not consider the reduced consumption of oil and gas for space heating that would result from warmer temperatures.

Table 6-12 shows the percentage changes in electric power requirements for various areas in the Southeast. Along the Gulf coast, annual power requirements would increase 3-4% by 2010 and

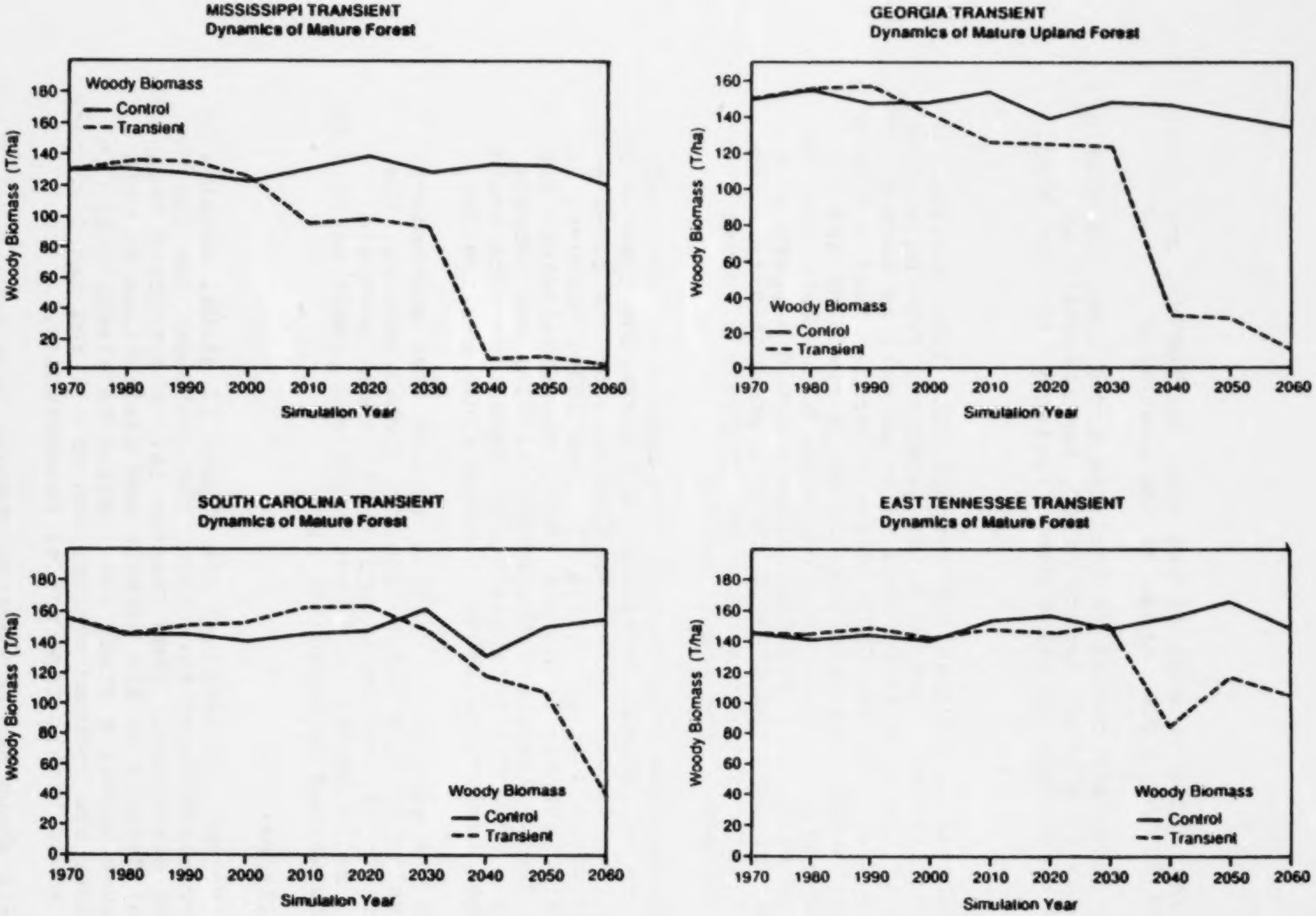


Figure 6-17. Southeastern response of forests to GISS transient scenarios or climate change.

Source: Urban and Shugart, Volume __.

Table 6-12. Percentage Increases in Peak and Annual Demand for Electricity by 2010 and 2055 Due to Climate Change

	GISS A (2010)		GISS B (2010)		GISS A (2055)	
Area	Annual	Peak	Annual	Peak	Annual	Peak
North Carolina, South Carolina, Georgia	1.6	7.3	1.3	2.4	5.9	24.4
Florida	2.7	4.9	2.7	3.6	9.3	20.0
Eastern Tennessee	1.6	3.7	1.3	1.2	5.9	12.2
Alabama, Western Tennessee	1.9	3.8	2.2	5.7	6.8	13.5
Mississippi	3.8	7.6	4.4	11.4	13.6	26.9
Louisiana	2.9	7.6	2.7	6.6	10.2	23.4
East Texas	3.1	7.9	2.8	6.6	11.3	25.3

Source: Linder and Inglis, Volume __.

10-14% by 2055; elsewhere, the increases would be somewhat less. Because peak demand for electricity generally occurs during extremely hot weather, peak demand would rise more than annual demand. Global warming could increase new generating capacity requirement 10-24% by 2010 and 24-34% by 2055.

Linder compared increases in electric capacity required by climate change with those necessitated by economic growth. He estimated that through 2010, climate change could increase the expected capital costs of $137 billion 6 to 9%; through 2055, it could increase expected requirements of $350-500 billion by as much as 20%.

OTHER STUDIES

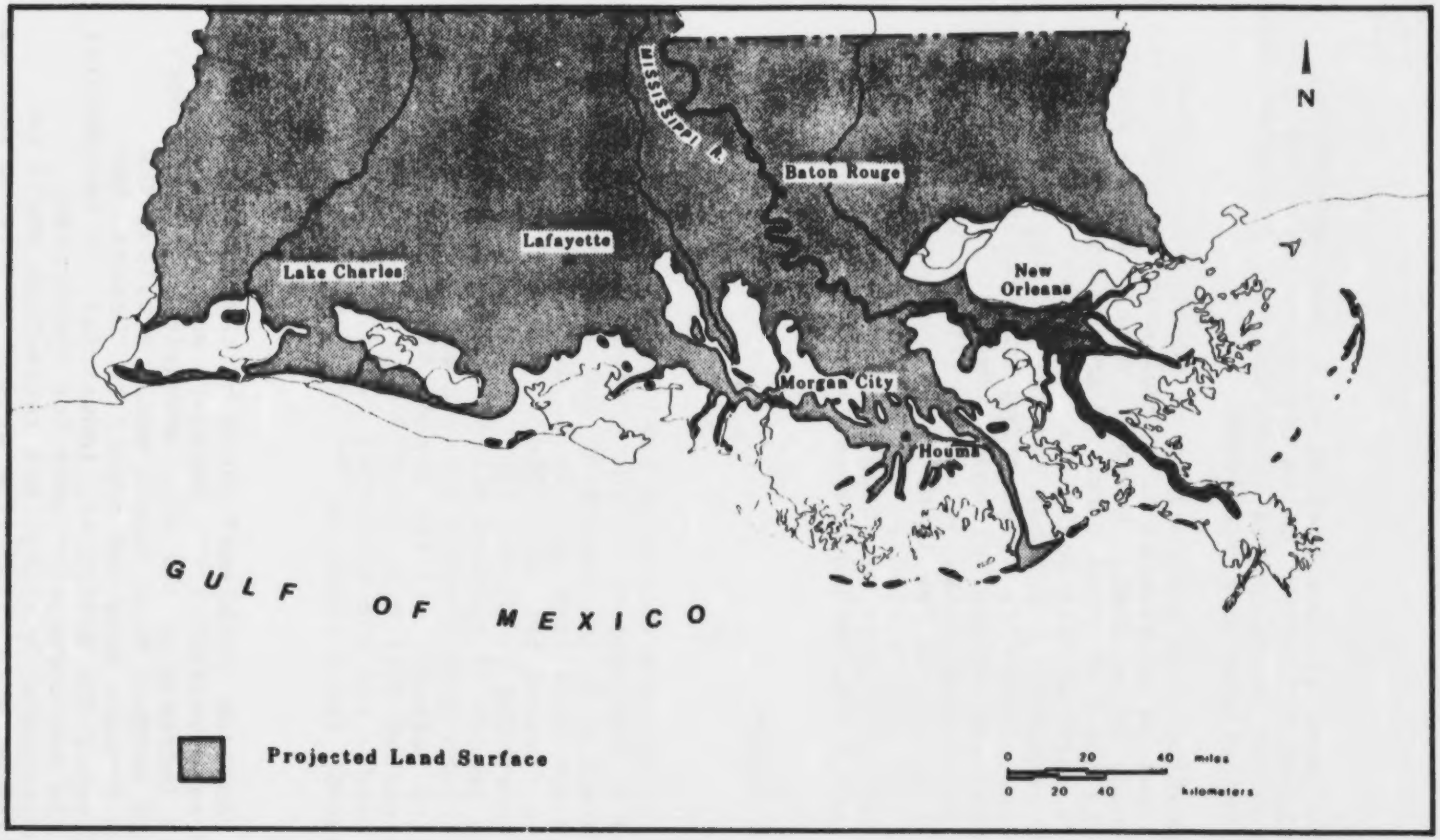
Coastal Louisiana

An estuary accounting for half of the Southeast's wetlands is also the most vulnerable: the delta at the mouth of the Mississippi River. Because previous studies assessed the vulnerability of Louisiana in detail, the current effort supported no additional research into this issue.

Over the last few thousand years, the sediment washing down the Mississippi River has formed the nation's largest delta at the river's mouth, almost all of which is in Louisiana. Composed mostly of marsh, cypress swamps, and small distributary channels that carry water, sediment, and nutrients from the river to these marshes and swamps, Louisiana's wetlands support half of the nation's shellfish, one-fourth of its fishing industry, and a large trapping industry. They also provide flood protection for metropolitan New Orleans and critical habitats for bald eagles and other migratory birds.

Water management and other human activities of the last 50 years are now causing this delta to disintegrate at a rate of over 100 km^2 (about 50 km^2) per year. The delta has always subsided as the sediment compacted, but the rate of sinking was more than balanced by new sediment reaching the wetlands through the distributaries and the annual river flooding. But that sediment now largely washes into the deep waters of the Gulf because flood-control and navigation guide levees confine the flow of the river. Thus, the delta is gradually being submerged, and cypress swamps are converting to open-water lakes as saltwater penetrates inland. If current trends continue, almost all of the wetlands will be lost in the next century.

A rise in sea level would further accelerate the rate of land loss in coastal Louisiana. As shown in Figure 6-18, even a



N
Baton Rouge
Mississippi R.
Lafayette
Lake Charles
New Orleans
Morgan City
Houma
GULF OF MEXICO
Projected Land Surface
0 20 40 miles
0 20 40 kilometers

Figure 6-18. Projected Future Coastline of Louisiana for the Year 2033 A.D. Given a Rise in Sea Level of 55 cm as Predicted in the High Scenario

Source: Louisiana Wetland Protection Panel, 1987.

50-cm rise in sea level (in combination with land subsidence) would inundate almost all of the delta and would leave New Orleans, most of which is below sea level and only protected with earthen levees, vulnerable to a hurricane.

Strictly speaking, the entire loss of coastal Louisiana's estuaries should not be attributed to global warming because the ecosystem is already being lost. However, major efforts are being initiated by the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, the Louisiana Geological Survey, several local governments, and other Federal and state agencies to curtail the loss, generally by erecting structures to provide freshwater and sediment to the wetlands. Technical staff responsible for developing these solutions generally fear, however, that a 1-m rise in sea level could overwhelm current efforts, and that if such a rise is ultimately going to take place, they already should be planning and implementing a much broader effort (Louisiana Wetland Protection Panel, 1987).

IMPLICATIONS AND POLICY

Land Use

The impact of climate change on land use in the Southeast must be examined in the context of the projected abandonment of 10-50% of the farmland in the Southeast and declines in forests. A major issue is how this land will be used. In the past, forests have been cleared for agriculture, and when abandoned, they have been converted to forest again. But the forest models suggest that the impact of climate change on the generation of new forests from bare ground would be even more adverse than the impact on existing forests. If the forest simulations are correct, the abandoned fields would become grasslands or overgrown with weeds, and the Southeast could gradually come to resemble the scenery found today in the Great Plains.

Water Resources

The water resource "problems" faced by the Southeast are the type that would make western water managers envious. Rainfall and runoff would increase in the GISS scenario. Although most other assessments suggest that runoff would decline, the magnitude of the decline does not appear to threaten the availability of water for municipal, industrial, or residential use. However, the nonconsumptive uses for hydropower, navigation, environmental quality, and recreation could be threatened. Although sufficient time exists to develop rational strategies to implement the necessary tradeoffs, current Federal statutes in a rigorous fashion discourage water managers from formally considering them.

Impacts of Wetter Climate

Although most water resource problems have been associated with too little water, it does not necessarily follow that a wetter climate would be generally beneficial. The designs of water management infrastructure and the location of development along lakes and rivers have been based on current climate. Hence, shifts in either direction would create problems.

The chief problem from a wetter climate would be more flooding, particularly in southern Florida and coastal Louisiana, where water often lingers for days and even weeks after severe rainstorms and river surges. Inland communities, such as Chattanooga, also might face flooding if wetter periods exceed the ability of dams to prevent flooding.

Impacts of Drier Climate

A drier climate, on the other hand, would exacerbate current conflicts over water use during dry periods. Hydropower would decline, increasing the need to use fossil or nuclear power, both of which would require more water for cooling. Conflicts between municipal water users and recreational interests also would intensify. Lake levels could drop more during the summer, even if municipal use of water did not grow. However, warmer temperatures probably would increase municipal water demand for cooling buildings and watering lawns.

These conflicts could be further exacerbated if farmers increase the use of irrigation. Groundwater is available in reasonably shallow aquifers that drain into rivers. Any consumptive use of water from these aquifers would reduce, and in some cases reverse, the base flow of water from aquifers into these rivers. Water also could be drawn directly from rivers for irrigation in some areas.

A decline in riverflows could be important for both navigation and environmental quality. For the Tennessee, as well as the Chattahoochee and other small rivers, adequate reservoir capacity exists to maintain flows for navigation, if this use continues to take precedence over water supply and recreation. However, the 1988 drought has graphically demonstrated that there are not enough dams to guarantee navigation in the Mississippi. If this situation became more commonplace, the economic impact on New Orleans could be severe. On the other hand, traffic on the Tennessee and Ohio Rivers might use the Tennessee-Tombigbee Canal as an alternative, which would benefit the port of Mobile.

Lower flows also would reduce the dilution of municipal and industrial effluents discharged into rivers and would decrease the level of dissolved oxygen. This would harm fish populations directly, and indirectly by reducing the abilities of streams to assimilate wastes. Reduced flows also would threaten bottomland hardwood and estuarine ecosystems. To prevent these problems, factories and powerplants might have to more frequently erect cooling towers or curtail their operations.

Is Current Legislation Adequate?

The same issues that face the TVA and Lake Lanier would likely face decisionmakers in other areas. Federal laws discourage water managers in the Southeast from rigorously evaluating the tradeoffs between the various uses of water. Most dams are more than sufficient to meet the statutory requirements for navigation and flood safety and to continue generating substantial hydropower on demand. Consequently, there has been little need to analyze the tradeoffs between these factors. For example, a literal application of the law would not allow the Corps of Engineers to cut hydropower production or navigation releases to ensure a supply of water for Atlanta. Therefore, agencies have not analyzed the allocation of water that best serves the public for various levels of water availability (although the TVA is beginning to do so).

At a practical level, Federal water managers have shown flexibility, as in the case of cutting navigation along the Chattahoochee instead of further cutting Atlanta's water supply. If climate changes and more than a modest level of flexibility is necessary, water resource laws could be changed; the physical infrastructure is largely in place to address water problems of the Southeast. But until the laws are changed, the Federal agencies in the Southeast often would be forced to allocate water inefficiently. Moreover, people making decisions concerning siting of recreational and industrial development, long- term water supply sources, powerplant construction, and other activities sensitive to the availability of water would risk basing their decisions on incorrect assumptions regarding the future allocation of water.

Estuaries

Coastal plants and animals across the Southeast may have difficulty surviving warmer temperatures. For example, along the northern coast of the Gulf of Mexico, several types of fish spend at least part of their lifetimes in estuaries that are already as hot as they can tolerate. If climate becomes warmer, however, migrating north would not be feasible. While these species could escape the summer heat by fleeing to the cooler waters of the gulf, such a flight would make them vulnerable to larger fish.

Although the gulf coast estuaries are the warmest, estuaries as far north as North Carolina reach temperatures only about 3° cooler than those that prevail in the Apalachicola estuary. Thus, all southeastern estuaries are likely to lose at least as great a proportion of their oysters, shrimp, and crabs to high temperatures as the Apalachicola loses today, and most would lose more.

In addition to the direct effect of climate change on estuaries, human responses to climate change and sea level rise also could hurt coastal estuaries. The flood control works erected in response to disasters in Florida and along the Mississippi River now appear to be destroying the Everglades and coastal wetlands of Louisiana. Additional flood control levees and bulkheads to stop erosion could result in additional wetland loss, as discussed in Chapter 9: Sea Level Rise. Increased reservoir construction would decrease the amount of sediment flowing down the river and nourishing the wetlands. If the climate becomes drier, irrigation could further reduce freshwater flow into estuaries.

To a large extent, the policy implications for wetland loss in the Southeast are similar to those facing the rest of the U.S. coastal zone. Previous studies have identified several measures to reduce the loss of coastal wetlands in response to sea level rise (e.g., Office of Wetland Protection, 1988; Titus, 1988). These measures include the following:

- increase the ability of wetlands to keep pace with sea level,
- remove impediments to landward creation of new wetlands, and
- dike the wetlands and artificially maintain water levels.

All of these measures are being employed or actively considered.

Congress has authorized a number of freshwater and sediment diversion structures to assist the ability of Louisiana's wetlands to keep up with relative sea level rise. These structures are engineered breaches in river levees that act as spillways into the wetlands when water levels in the river are high. Although decisions on where to build diversion structures are being based on current climate and sea level, consideration of global warming would substantially change the assumptions on which current analyses are being based and the relative merits of alternative options. More frequent or higher surges in the Mississippi River would increase the amount of water delivered to the wetlands. And if climate change resulted in more soil erosion, more sediment might also reach the wetlands; lower flows could have the opposite effect. Sea level rise might shorten the useful lifetimes of these projects, but because the flood-protection benefits of protecting coastal wetlands would be greater with a higher sea level, the economic justification of these projects would not necessarily be undermined by the prospect of sea level rise. Nevertheless, they would change the relative merits of alternative options (Louisiana Wetland Protection Panel, 1987).

Artificially managing water levels also has been proposed for Louisiana, particularly by Terrebonne Parish, whose eastern wetlands are far removed from a potential source of sediment. Such an approach also might be possible for parts of Florida, where wetlands already are confined by a system of dikes and canals, and water levels already are managed. Although no one has yet devised a practical means by which shrimp and other fish could migrate between ocean and estuary, other species spend their entire lifetimes within the estuary, and freshwater species could remain in artificially maintained freshwater wetlands.

A final response would be to accept the loss of existing wetlands, but to take measures to prevent development from blocking the landward creation of new wetlands. This approach has been enacted by the state of Maine (1987) and would be consistent with the proposals to discourage bulkheads that have been widely discussed by coastal zone managers and enacted by the state of South Carolina. Titus Greene estimates that 1800 mi^2 of wetlands in the Southeast could be created if developed areas were not protected. Although this area represents a small fraction of the potential loss, it would increase the remaining areas of wetlands by 30-90%, and it would maintain and perhaps increase the proportion of shorelines on which at least some wetlands could be found.

Beach Erosion

The implications of sea level rise for recreational beaches in the Southeast are similar to the implications for the mid-Atlantic and the Northeast. If shore-protection measures are not taken, the majority of resorts will have no beach at high tide by 2025 under the midrange scenario of future sea level rise. The cost of undertaking the necessary measures through 2025 would probably be economically justified for most resorts (see Chapter 9: Sea Level Rise). However, the cost of protecting all recreational beaches through 2100 would be $100 to $150 billion, which would probably lead some of the more vulnerable areas to accept a landward migration much as areas on North Carolina's Outer Banks are facing today.

The potential responses to global warming should be viewed within the context of current responses to erosion flooding. Florida has a trust fund to nourish its beaches and has received Federal assistance for pumping sand onto the shores of Miami Beach. Although Mississippi has no reason to combat the landward migration of its barrier islands, it has nourished the beaches of Biloxi, Gulfport, and other resort communities that lie on the mainland along the protected waters behind the barriers. Louisiana is rebuilding its undeveloped barrier islands because they protect the mainland from storms. Most states have employed a variety of structural solutions, such as groins (jetties) and seawalls. However, they are moving toward "soft engineering" solutions, such as beach nourishment, because of doubts about the effectiveness of hard structures in universal erosion and their interference with recreational uses of the beach.

Land-use measures also have been employed to adapt to erosion. Because of unusually high erosion rates on the Outer Banks, houses along the coast are regularly moved landward. North Carolina requires houses, hotels, and condominiums to be set back from the shore by the distance of a 100-year storm plus 30 years' worth of erosion on the assumption that after 30 years, the house could be moved back. To maintain the integrity of its publicly owned recreational beaches and to discourage shorefront property owners from expecting state efforts to protect these beaches, Texas requires that any house left standing in front of the vegetation line after the shore erodes must be torn down.

If a global warming increases the frequency of hurricanes, a number of southeastern communities will be devastated. There is no way to know which communities might experience a hurricane resulting from the greenhouse effect. However, the overall impact of increased hurricane frequency would be small compared to the impact of sea level rise. While a doubling of hurricanes would convert 100-year floodplains to 50-year floodplains throughout much of the Southeast, a 1-m rise would convert them to 15-year floodplains.

Because the open-coast areas most vulnerable to sea level rise are generally recreational beach resorts, the costs of erosion and flooding should be viewed within the larger context of why people go to the beach. People from the north visit southeastern beaches to escape winter, and residents of the region go to escape the summer heat. As temperatures become warmer, Georgia and the Carolinas will be able to compete with Florida for northerners. Hotter temperatures also may increase the desire of the region's residents to visit the beach.

Thus, it is possible that the cooler communities will reap benefits from a longer and stronger tourist season that are greater than the increased costs for erosion control. Areas that already have a year-round season are less likely to benefit, and in a few areas like Miami Beach, the off-season may be extended.

REFERENCES

Armentano, T.V., R.A. Park, and C.L. Cloonan. 1988. Impacts on Coastal Wetlands Throughout the United States." In Titus (ed) 1988. op. cit.

Barth, M.C. and J.G. Titus. 1984. Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Bureau of Economic Analysis. Department of Commerce. 1986.

Bureau of the Census. Department of Commerce. 1982 Census of Agriculture. Vol. 1. Geographic Area Series.

Bureau of the Census. Department of Commerce. 1988. Statistical Abstract of the United States: 1988.

Burnash Robert J.C., R. Larry Ferral, and Richard A. Mcguire. 1973. "A Generalized Streamflow Simulation System, Conceptual Modeling for Digital Computers." National Weather Service and California Department of Water Resources. Sacramento, California.

Edison Electric Institute. 1985. Statistical Yearbook of the Electric Utility Industry.

Energy Information Administration. May 1988. Electric Power Monthly.

Fisheries Statistics Division, National Marine Fisheries Service, NOAA. 1987 Preliminary Statistics for United States Domestic Catch.

Geraghty, J., D. Miller, F. Van Der Leeden, and F. Troise. 1973. Water Atlas of the United States. Water Information Center, Port Washington, N.Y.

Gibbs, M. 1984. Economic analysis of sea level rise: Methods and results. In Barth and Titus 1984.

Healy, Robert G. 1985. Competition for Land in the American South. Washington, D.C.: The Conservation Foundation.

Jenkins, Representative, Rep. Barnard, and Rep. Darden. 1988. HR-4254: Georgia Resevoir Management Act of 1988. 100th Congress. 2nd session.

Jones, C.A. abd J.R. Kiniry (eds.). 1986. CERES-Maize: A simulation model of maize growth and development. College Station, Texas: Texas A&M Press.

Kana, T.W., J. Michel, M.O. Hayes, and J.R. Jensen. 1984. The physical impact of sea level rise in the area of Charleston, South Carolina. In Barth and Titus (eds) 1984.

Leatherman, S.P. 1984. Coastal geomorphic responses to sea level rise: Galveston Bay, Texas. In Barth and Titus (eds) 1984.

Linder, K.P., M.J. Gibbs, and M.R. Inglis. 1988. Potential Impacts of Climate Change on Electric Utilities. New York, N.Y.: New York State Energy Research and Development Authority.

Louisiana Wetland Protection Panel. 1987. Saving Louisiana's Coastal Wetlands: The Need for a long-term Plan of Action. Washington, DC: U.S. Environmental Protection Agency/Louisiana Geological Survey. EPA-230-02-87-026.

Meo, M. 1987. Proceedings of the Symposium on Climate Change in the Southern United States. Norman, OK: University of Oklahoma.

Mitch, W. and J. Gosselink. 1986. Wetlands. New York: Van Nostrand Reinhold Company, Inc.

Shugart, H.H. and D.C. West. 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. Journal of Environmental Management. 5:161-179.

Titus, J.G., C.Y. Kuo, M.J. Gibbs, T.B. LaRoche, M.K. Welts, and J.O. Waddell. 1987. Greenhouse effect, sea level rise, and coastal drainage systems. J. Water Res. Planning and Management ASCE 113(2):216-227.

Titus, J.G. 1987. "The Greenhouse Effects, Rising Sea Level, and Society's Response." In: R.J.N. Devoy. 1987. Sea Surfact Studies Croom Helm: New York.

Titus, J.G. 1988. Greenhouse Effect, Sea Level Rise, and Coastal Wetlands. Washington, D.C.: U.S. Environmental Protection Agency.

Titus, J.G. 1988. "Sea Level Rise and Wetland Loss: An Overview." In Titus (ed). op. cit.

Titus, J.G. 1984. Planning for Sea Level Rise Before and After a Coastal Disaster. In: Barth, M.C. and Titus, J.G. (eds).

Greenhouse Effect and Sea Level Rise: A Challenge for This Generation. New York: Van Nostrand Reinhold Company.

Wilkerson, G.G., J.W. Jones, K.J. Boote, and J.W. Mishoe. 1985. SOYGRO V5.0: Soybean Crop Growth and Yield Model. Technical Documentation. Gainesville, FL: University of Florida.

Table 6-11. Impact of Climate Change on Cultivated Land in the Southeast

Region	Baseline	With Direct CO_2 GISS	With Direct CO_2 GFDL	Without Direct CO_2 GISS	Without Direct CO_2 GFDL
Acreage (millions)					
Southeast coast	12.5	8.7	7.8	11.5	11.2
Appalachia	15.5	2.8	7.4	14.1	12.9
Delta	19.9	9.3	16.7	17.7	16.2
Total	47.9	20.8	31.9	43.3	40.3
Percent loss					
Southeast coast		30	38	8	10
Appalachia		82	52	9	17
Delta		53	16	11	19
Total		57	33	10	16

Note: SE coast includes Florida, South Carolina, Georgia, Alabama.
Appalachia includes North Carolina, Tennessee, Virginia, West Virginia, Kentucky.
Delta includes Mississippi, Louisiana, Arkansas.

DRAFT

CHAPTER 7

GREAT PLAINS

FINDINGS

Global warming in the Great Plains may reduce agricultural output, increase irrigation demand, change water quality, and increase electricity needs.

Agriculture

- Generally, the effects of a warmer climate alone would reduce wheat and corn yields. Yield changes range from +15 to -90%. The direct effects of CO_2 on crop photosynthesis and water use may mitigate these effects, unless climate change is severe.
- Crop yields in southern areas, such as Texas and Oklahoma may decline relative to northern areas of the United States. This change in productivity could lead to a 4 to 22 percent reduction in cultivated acreage in the Great Plains.
- Because of the increased reliability of yields from irrigated lands relative to dryland yields, and because of higher crop prices, demand for irrigation water on remaining farms will probably increase. The number of acres irrigated may increase by 5 to 30 percent.

Water Quality

- Water quality in the southern Great Plains would be altered due to changing pesticide loadings in surface runoff and erosion. Quality of groundwater may be less at risk than surface water quality, because of increased evaporation and less leaching. These results are very sensitive to changes in the amounts and frequency of rainfall.

Electricity Demand

- The annual demand for electricity in Kansas, Nebraska, Oklahoma, and West Texas could rise by 5 to 10 billion kilowatt hours (2 to 4 percent) by 2010 and by 41 to 81 BKWH (10 to 14 percent) by 2055.
- By 2010, approximately 3 to 6 gigawatts would be needed to meet the increased demand and by 2055, 22 to 45 GW would be needed -- a 27 to 39 percent increase over baseline additions that may be needed without climate change -- the cumulative cost of these additions by 2055 would be $24 to $60 billion.

- Agencies with responsibility for agricultural land use, such as the USDA Agricultural Stabilization and Conservation Service and the Soil Conservation Service, could begin to analyze how their missions may be affected by climate change and to consider development of flexible strategies to deal with potential impacts. Water resource managers, such as those on the River Basin cimmissions and in State natural resource agencies, may wish to factor the potential effects of cllimate change into planning of long-term irrigation, drainage, and water-transfer systems.

CLIMATE-SENSITIVE ASPECTS OF THE GREAT PLAINS

Agriculture

The Great Plains consist of a treeless region of relatively flat topography between the Rocky Mountains and the Mississippi lowlands of central North America. Since agricultural settlement began in the late 1800s, the area has developed into a key small-grains agricultural production region. The southern Great Plains developed rapidly as a wheat production area and became an extensive dryland agricultural region dominated by the cultivation of wheat (Figure 7-1). In the last two decades, exploitation of water from the Ogallala Aquifer has led to the development of significant irrigated agricultural production. In many areas, irrigated farming of corn, rice, and cotton has replaced dryland wheat production, especially in western Kansas and the Texas Panhandle (Figure 7-1).

The Great Plains portions of Kansas, Nebraska, Oklahoma, and Texas constitute a vital part of the United States' agricultural base. Nearly 100,000 farms encompassing over 111 million acres produce an important array of dryland and irrigated crops. Major dry farming crops include winter wheat and grain sorghum, and irrigated grains include corn and rice. In all, the four States produce over 80, 40, and 15%, respectively, of the nation's grain sorghum, wheat, and corn (Table 7-1).

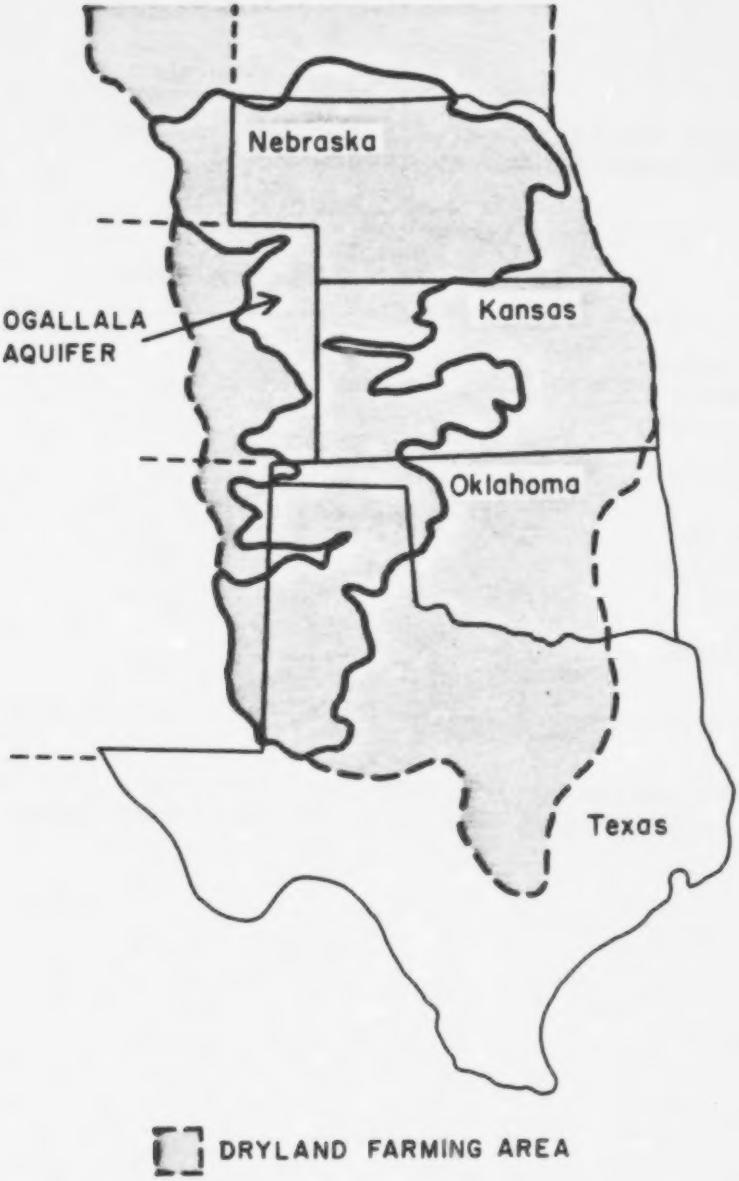

Nebraska
OGALLALA AQUIFER
Kansas
Oklahoma
Texas
DRYLAND FARMING AREA

Figure 7-1. Dryland wheat production in Great Plains.

Source: Science of Food and Agriculture (1987, 1988).

TABLE 7-1. U.S. Agricultural Ranking and Percent of U.S. Total for Selected Products, 1982.

	Kansas	Nebraska	Oklahoma	Texas	% U.S. Total
Sorghum harvested	2	3	5	1	80.5
Cattle fattened on grain and concentrates sold	2	3	9	1	46.7
Value of cattle and calves sold	2	3	7	1	40.7
Wheat harvested	1	9	3	6	31.8
Cotton harvested			9	2	25.8
Hay harvested	9	2	16	7	15.9
Market value of all agricultural products	6	5	20	3	18.5

Source: 1982 Census of Agriculture. U.S. Bureau of the Census. 1983. U.S. Government Printing Office. Washington, D.C.

Livestock constitute another important agricultural commodity in the region. Almost 50% of all cattle fattened in the country are raised in the four States, accounting for 40% of the total U.S. value of marketed livestock.

In addition to contributing substantially to national production, the four States are also major exporters of agricultural products. Foreign exports of grain and animal products are especially notable (Table 7-2). In total, these four States provide approximately one-fifth of the dollar value of all U.S. agricultural exports. Yet, dependence on foreign markets puts Great Plains farmers at high risk. While large historical fluctuations in grain and livestock production levels are partly related to climatic variability, changing international markets have also played an important role in the region's failure to achieve long-term economic and social stability.

Farmers in the Great Plains have been particularly vulnerable to climate variability. The southern and central Great Plains States of Nebraska, Kansas, Oklahoma, and Texas, the focus of this regional case study, were among the hardest hit during the Dust Bowl of the 1930s (Worster, 1979; Hurt, 1981). Yields of wheat and corn dropped as much as 50% below normal, causing the failure of about 200,000 farms and migration of more than 300,000 people from the region.

The Dust Bowl, other droughts, and the desire for continued expansion and intensification of dryland farming have led to numerous technological and social adjustments to climate and market fluctuations. Especially critical, from a dryland farming perspective, has been the improvement of conservation tillage practices (Warrick and Bowden, 1981; Riebsame, 1983). These practices, now prescribed for the area, aim to conserve moisture, reduce energy input, and minimize erosion, thus increasing yields and profits.

Besides the developments in cropping systems, policies have also been devised to absorb or mitigate the impacts of climate stresses. These include Federal programs for crop insurance, disaster grants and low-interest loans to farmers, and Government-sponsored drought research (Warrick, 1980). Such programs can be costly. For example, the Drought Relief Bill proposed for the current drought of 1988 is projected to cost about $3.9 billion nationally (New York Times, 1988).

Table 7-2. Agricultural Exports from Selected Plains States, Fiscal Year 1984 (Millions of Dollars).

	U.S.	Kansas	Nebraska	Oklahoma	Texas	% U.S. Total
Feed grains and products	7,585	372	903	-	385	22
Wheat and products	4,526	797	150	353	276	35
Live animal and meats	1,161	130	134	18	161	38
All agricultural products	31,187	1,719	1,762	71	2,031	19

Source: USDA Economic Research Service. 1985. Foreign Agricultural Trade of the United States. Washington, D.C.

The Great Plains is one of the most marginal agricultural regions in the United States. Some observers feel that the southern Plains are simply too sensitive to climatic swings and that intensive dryland farming should be abandoned (Worster, 1979). Yet in a wet year, the Plains produce bumper crops of small grains that add significantly to the nation's export trade balance.

Despite the adoption of conservation tillage techniques, drought-resistant cultivars, and risk management programs, some analysts argue that the region remains particularly vulnerable to climate-induced reductions in crop yields and might manifest the first impacts of climate change (e.g., Lockeretz, 1978). Rapid acreage increases in the 1970s, destruction of windbreaks for larger fields to accommodate bigger machinery, and speculative farm expansion all raise the specter of renewed land degradation similar to that of the Dust Bowl period, if climate change creates an increased frequency of heat waves and droughts in the region.

The Ogallala Aquifer

A major response to the semiarid and highly variable climate of the Great Plains has been exploitation of surface and groundwater resources for irrigation. In 1982, 75,000 km^2, or 12% of all Great Plains cropland, were irrigated. Groundwater provides most of the water for irrigation: 61-86% of the water used in Nebraska, Oklahoma, and Kansas compared with only 20% nationally.

The improvement and application of well drilling and pumping technology after World War II permitted the use of water from the immense Ogallala Aquifer (Figure 7-1). Today, the aquifer supplies irrigation for approximately 14 million acres in the Great Plains States of Colorado, Nebraska, Kansas, Oklahoma, New Mexico, and Texas (High Plains Associates, 1982). Use of the aquifer allows the irrigation of upland terrain previously too far from surface supplies. The aquifer also provides water for municipal and industrial purposes.

Nebraska recently started to use the aquifer to irrigate corn, which is grown mostly for livestock feed. Corn, wheat, and some sugar beets are irrigated further south, while in Texas the Ogallala is tapped chiefly for cotton. The aquifer varies in its depth from the surface of the land, its rate of natural discharge, and its saturated thickness in different regions. Nebraska has a higher recharge rate (i.e., the rate at which the aquifer is replenished) than the other Great Plains States and has not yet suffered significant drawdown problems. In Texas, high withdrawal and low recharge rates of the aquifer have already resulted in "mining" of the resource (i.e., the rate of water withdrawal is greater than rate of recharge) and in the abandonment of thousands of irrigated acres (see Wilhite, Volume _).

PREVIOUS CLIMATE CHANGE STUDIES

Several studies of climate change impacts on agriculture in the Great Plains have been performed, using a variety of approaches and models. Warrick (1984) considered the vulnerability of the region to a possible recurrence of the 1930s drought. Using a crop yield model tuned to 1975 technology, Warrick found that a recurrence of 1934 and 1936 conditions on the Plains would result in wheat yield reductions of over 50%.

Terjung et al. (1984) investigated water regimes for corn production under differing climate change scenarios, using a crop water-use and yield model. They found that the middle latitudes of the Great Plains were the most sensitive to the climate change scenarios both in evapotranspiration and total water applied for irrigation. This modeling work was continued by Liverman et al. (1986), who found that the lowest irrigated yields occurred under cloudy, hot, and very dry climate change scenarios. Under dryland conditions, minimum yields occurred under sunny-hot and sunny-warm scenarios with very dry conditions.

Using an agroclimatic approach, Rosenzweig (1985) found that lack of cold winter temperatures in the southern Great Plains may necessitate a change from winter to spring wheat cultivars. Decreased water availability may also increase demand for irrigation. In a later study, Rosenzweig (1987) showed that although the combined effects of climate change and increased CO_2 compensated for the negative effects of climate change in years with adequate rainfall, many simulated crop failures occurred in years with poor weather.

Robertson et al. (1987) estimated the combined impact of climate change and increased CO_2 on corn and wheat yields and erosion using the Erosion Productivity Impact Calculator (EPIC). Modeled wheat yields in Texas decreased and modeled corn yields increased only marginally due to moisture stress.

Glantz and Ausubel (1984) suggested that the Great Plains' mining of the Ogallala Aquifer and its susceptibility to future incidence of drought projected by global climate change models be combined in analyses of the region, since both are critical to the habitability of the area.

GREAT PLAINS STUDIES IN THIS REPORT

The EPA studies for this report examine the implications of climate change for agricultural production and economics, demand for irrigation water, and water quality. Climate change impact research on energy use and resource management policy relevant to the Great Plains are also described.

The studies performed for this report are listed in Table 7-3.

SUMMARY OF CLIMATE CHANGE SCENARIOS FOR THE GREAT PLAINS

The predicted changes in seasonal and annual temperatures and precipitation for all three scenarios are shown in Figure 7-2. All three scenarios show large increases in temperature for the Great Plains States under a doubled CO_2 climate. The GISS scenario has an average warming of 4.5°C, the GFDL scenario has a warming of 4.9°C and OSU has an average warming of 3.3°C. In general, winter temperatures increase more than summer temperatures in the GISS model, summer temperature changes are greater than winter temperature changes in the GFDL and OSU scenario. The studies used only the GISS and GFDL climate change scenarios.

Annual precipitation decreases by 0.26 mm/day in the GISS scenario, and 0.12 mm/day in the GFDL while OSU has a slight increase. However, these annual values mask a pronounced reduction in rainfall in Nebraska and Kansas in the GFDL scenario (see Figure 7-3). The large temperature increase and pronounced summer drying in these states combine to make the GFDL scenario more severe than the GISS scenario for the Great Plains.

The magnitudes of climate changes from the GFDL scenario and the climate of the 1930s drought in Nebraska and Kansas are compared in Figure 7-3. While the predicted decreases in precipitation are about the same as those during the most severe drought years (1934 and 1936) in the area, CO_2-induced temperatures are predicted to be about 3°C higher than the Dust Bowl temperatures.

Table 7-3. Great Plains Studies for EPA Report to Congress on the Effects of Global Climate Change

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Analyses Performed for This Case Study

- Potential Effects of Climate Change on Agricultural Production in the Great Plains: A Simulation Study

  Cynthia Rosenzweig
  Department of Geography, Columbia University
  NASA/Goddard Institute for Space Studies

- Effects of Projected CO_2-Induced Climatic Changes on Irrigation Water Requirements in the Great Plains States

  Richard G. Allen
  Utah State University

National Studies That Included Great Plains Results

- Economic Effects of Climate Change on U.S. Agriculture: A Preliminary Assessment

  Richard M. Adams
  Oregon State University

- Impacts of Climate Change on the Movement of Agricultural Chemicals Across the U.S. Great Plains and Central Prairie

  Howard L. Johnson
  Oklahoma Climatological Survey
  University of Oklahoma

- The Potential Impacts of Climate Change on Electric Utilities: Regional and National Estimates

  Kenneth P. Linder
  ICF Incorporated

- Adjusting Resource Management Policy to Climate Change

  William E. Riebsame
  University of Colorado

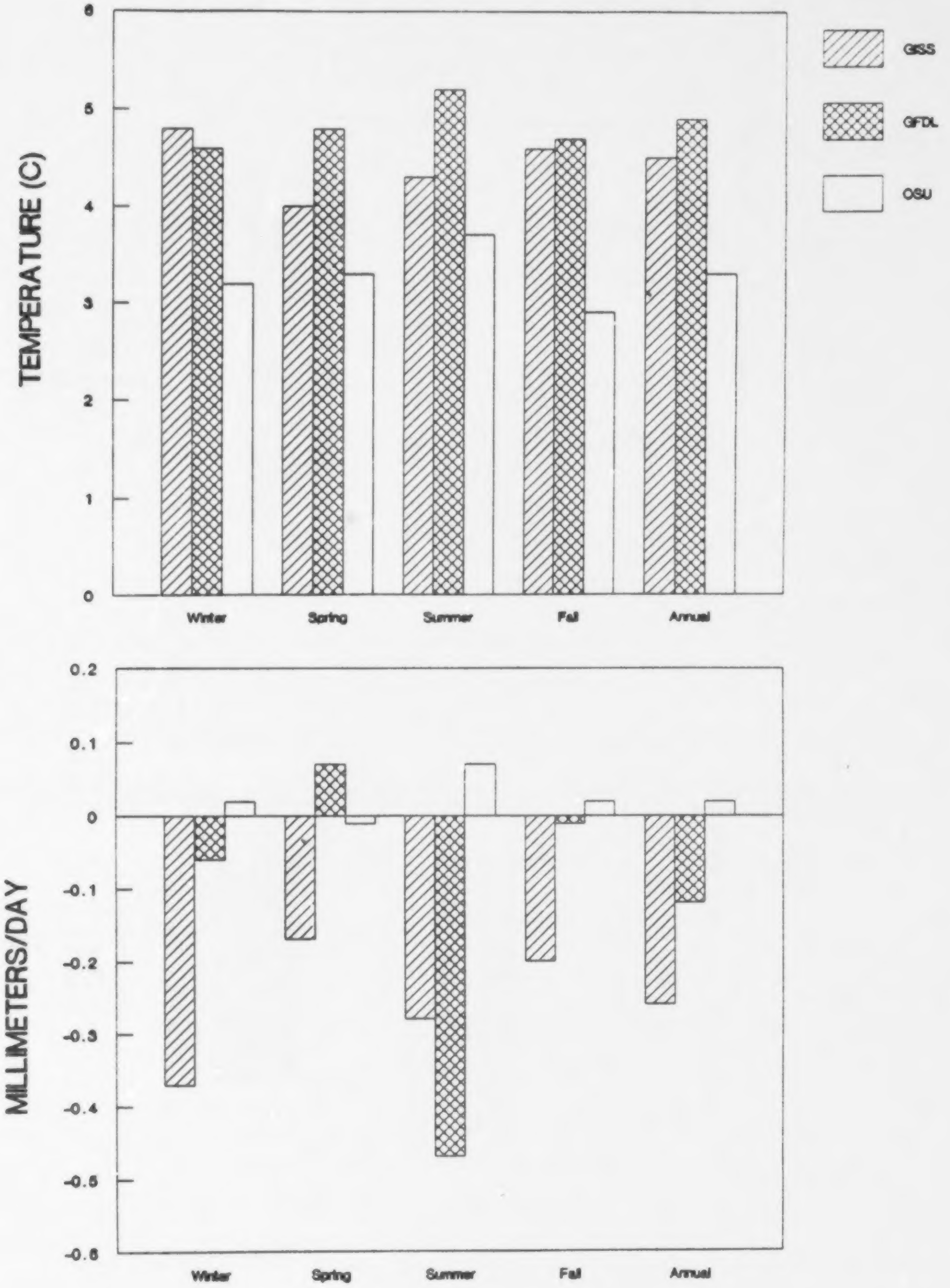
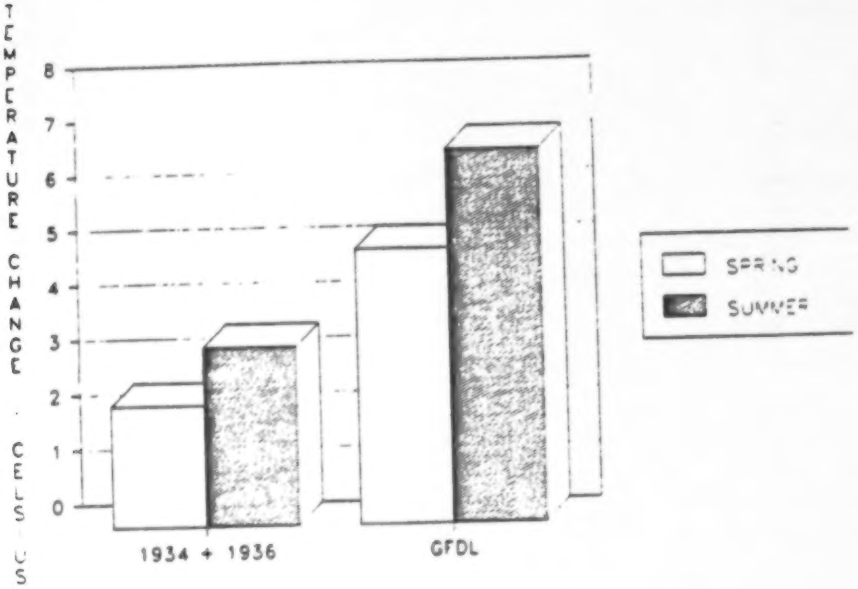


Figure 7-2. Average change in (a) temperature and (b) precipitation over Great Plains gridpoints ($2XCO_2$ less $1XCO_2$).



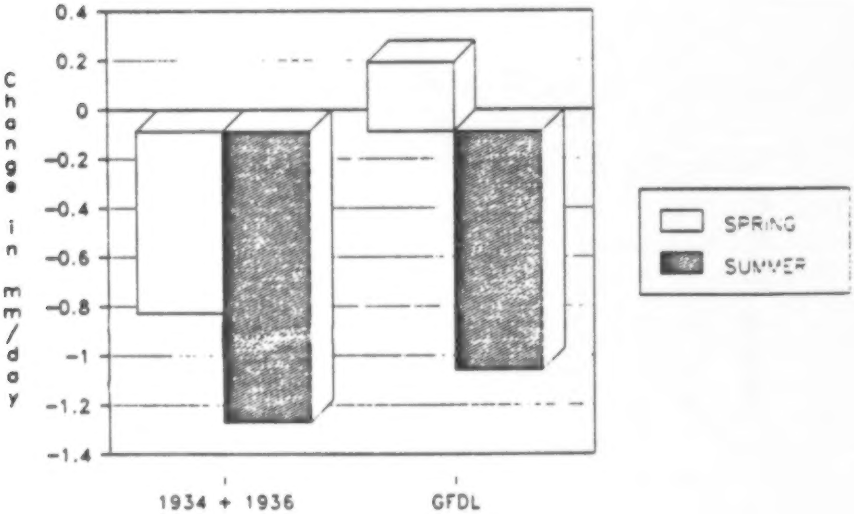


Figure 7-3. Comparison of observed drought and GFDL climate change for (a) temperature and (b) precipitation.

Chapter 7

RESULTS OF THE GREAT PLAINS STUDIES

Crop Production

To better understand the potential physical impact of climate change on crops, Rosenzweig modeled changes in corn and wheat yields in the Great Plains using crop growth models.

Study Design

The crop growth models, CERES-Wheat (Ritchie and Otter, 1985) and CERES-Maize (Jones and Kiniry, 1986), were used to test the sensitivity of crop yields to the GISS and GFDL climate change scenarios. These models are designed for large-area yield prediction and for farm decisionmaking.

They respond to a wide range of soil, climatic, and planting conditions. The models have a whole-plant framework.

At each of 14 locations, the crop models were run on three soils present in the region representing low, medium, and high productive capacity. Model results were generated for change of yield, water used for irrigation (if crop is irrigated), crop evapotranspiration, and planting and maturity dates for both dryland and irrigated cases.

The direct effects of CO_2, i.e., increased photosynthesis and decreased transpiration per unit leaf area, were simulated with the climate change scenarios in another set of runs. A method for approximating the direct effects was developed by computing ratios of daily photosynthesis and evapotranspiration rates of a canopy exposed to elevated CO_2 to the corresponding rates of the same canopy if exposed to ambient CO_2 conditions (see Peart et al., Volume _).

Limitations

This work does not consider changes in frequencies of extreme events, even though extremes of climatic variables, particularly runs of extremes, are critical to crop productivity (see Mearns, Volume _). Development of the CERES models was based on current climate; the relationships in the models may or may not hold under differing climatic conditions, particularly the high temperatures predicted for the greenhouse climate.

The direct effects of CO_2 are only approximated in the crop modeling study, because the models do not include a detailed simulation of photosynthesis. Also, experimental results from controlled environments may show more positive effects of CO_2 than will actually occur in variable, windy, and pest-infected (e.g., weeds, insects, and diseases) field conditions.

Results

Climate change scenarios cause simulated wheat and corn yields to decrease in the southern and central Great Plains. Decreases in modeled yields appear to be caused primarily by increases in temperature, which shorten the duration of crop life cycle (the period during which crops grow). This results in reduced yields. Wheat yields decrease more at lower latitudes. The changes in corn yields are displayed in Figure 7-4.

When the direct effects of CO_2 on crop photosynthesis and transpiration are included in the climate change simulations, modeled crop yields overcome the negative effects of climate change in some cases, but not in others (Figure 7-5). The more severe the climate change scenario, the less compensation provided by direct effects of CO_2.

The amount of water needed for irrigation increases in the areas where precipitation decreases. Irrigation appears to reduce interannual variability in yields.

Adjusting the planting date of wheat to later in the fall does not significantly ameliorate the effects of the GISS climate change scenario on CERES-Wheat yields. Changing to varieties with lower vernalization requirements (period of cold weather necessary for reproduction) and lower photoperiod sensitivity (sensitivity to daylength), in addition to delaying planting dates, overcomes yield decreases at some sites but not at others.

Implications

With high temperatures, increased irrigation may be needed to produce acceptable and stable yield levels. This could place increased demand on the already depleted Ogallala Aquifer and other water resources in the region.

Regional Agricultural Shifts

Many economic consequences are likely to result from the physical changes in crop yields and water availability caused by climate change. Adams et al. introduced yield changes from the Great Plains and other regional crop modeling studies and changes in water demand and availability from the GISS and GFDL scenarios into an economic model to translate the physical effects of

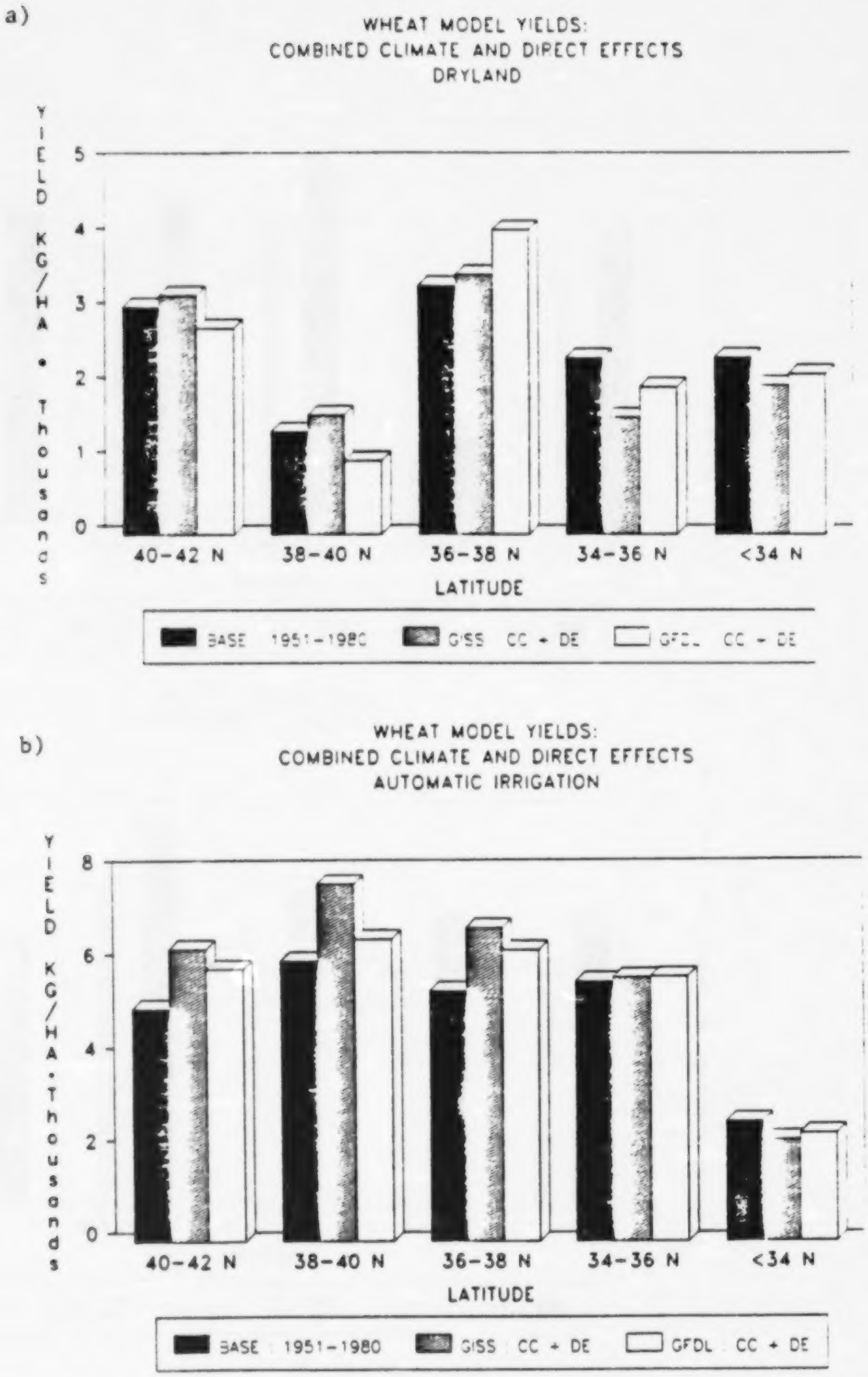
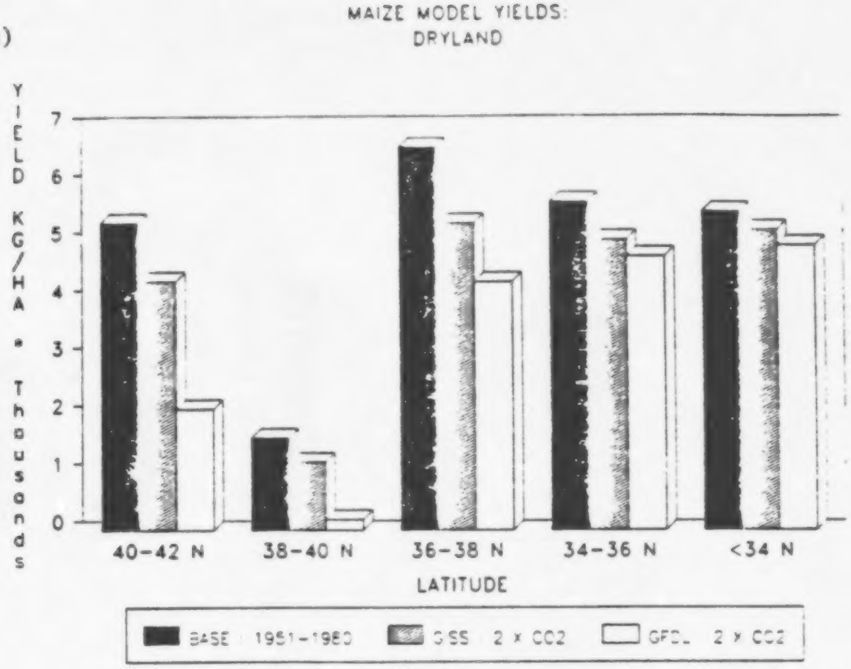


Figure 7-4. CERES-Wheat yields with climate change scenarios alone: (a) dryland (b) irrigated

Source: Rosenzweig, Volume __.

a)



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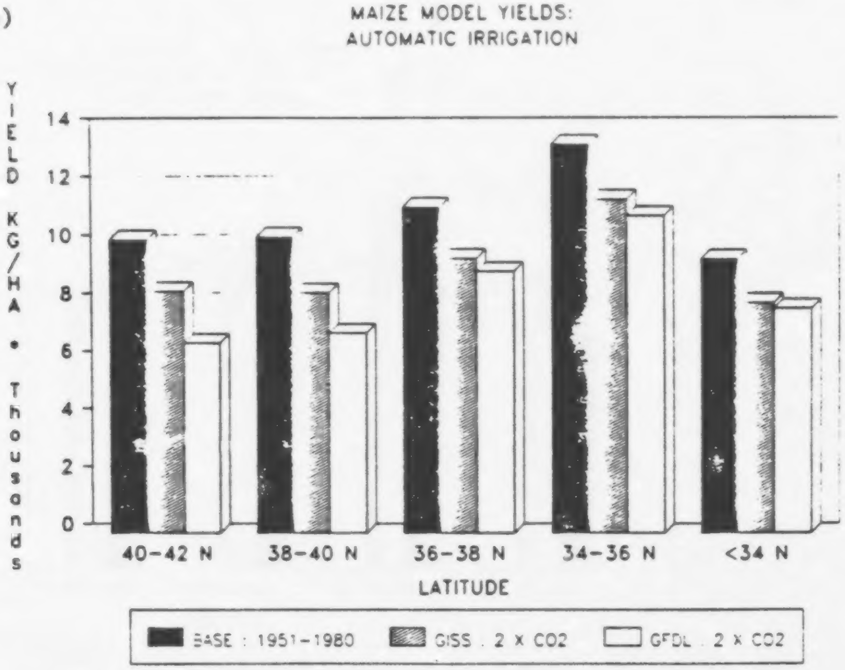

Figure 7-5. CERES-Maize yields with climate change and direct CO_2 effect: (a) dryland (b) irrigated

Source: Rosenzweig, Volume __.

climate change into economic consequences (see Chapter 10, Agriculture, for study design and limitations). Analyses were done both for climate change alone and for the combined effects of climate change and enhanced CO_2 concentrations. This analysis did not address the issues of whether the physical and institutional changes required to accommodate increased demand for irrigated acreage are feasible.

Regional Results

The estimates of Adams et al. (see Volume _) for total agricultural and irrigated acreage changes in the southern Great Plains States (Oklahoma and Texas only) are shown in Table 7-4. Agricultural land decreases in the southern Great Plains in all scenarios, both GISS and GFDL with and without the direct effects of CO_2. Decreases range from -22 to -4%. Irrigated acreage on the other hand increases in all scenarios, from 9 to 30%. This is because of increased stability in irrigated yields relative to dryland yields and a rise in commodity prices that makes expansion of irrigation production economically feasible. The higher limits of these ranges indicate the possibility of significant changes in the agriculture of the region.

Regional Implications

The results of the agricultural economics study imply that wheat and corn production may shift away from the southern Great Plains, causing dislocations of rural populations. For many rural communities in the region, this may further weaken an economic base already under pressure from long-term structural changes in U.S. agriculture.

If irrigated acreage does increase in the area, groundwater overdrafts also would be likely, along with associated increases in surface and groundwater pollution and other forms of environmental degradation.

Demand for Water for Irrigation

The projected higher air temperatures due to the growth of trace gases in the atmosphere may increase evaporative demands. Crop water use and irrigation water requirements are governed largely by the evaporation process.

Study Design

Allen and Gichuki (see Volume _) evaluated the effects of climate change and variations in canopy resistance on crop irrigation water requirements in the Great Plains. Allen and

Table 7-4. Changes in Land Usage in the Southern Plains (Millions of acres)

	Base Acreage	GISS			GFDL		
		Acreage	Change	%Change	Acreage	Change	%Change
NET LAND USE							
Without direct effects	54.7	42.6	-12.1	-22.1	52.0	-2.7	-4.9
With direct effects	54.7	48.8	-10.9	-19.9	52.7	-2.0	-3.8
IRRIGATED ACREAGE							
Without direct effects	5.3	6.9	1.6	+29.6	5.6	0.3	+4.9
With direct effects	5.3	5.8	0.5	+9.4	6.1	0.8	+15.3

Source: Adams et al., Volume __.

Gichuki used a soil water balance-evapotranspiration model to calculate daily soil moisture balances, evapotranspiration, and irrigation water requirements. The model employed the Penman-Monteith combination method to estimate crop evapotranspiration for corn, wheat, and alfalfa (Monteith, 1965). The model was run for four levels of potential direct effects of CO_2 on transpiration.

Limitations

Air temperature data at airport locations were adjusted to reflect temperature profiles to be expected over an irrigated crop field. This study assumed that alfalfa, corn, and wheat all would respond similarly to increased CO_2 (which may reduce transpiration), although published reports of experimental results show different responses among crops (see Rose, Volume _).

Results

The results indicate that irrigation requirements may increase or decrease, depending on the type of crop, changes in climatic factors and variations in canopy resistance. The perennial crop alfalfa showed persistent increases in seasonal net irrigation water requirements (see Figure 7-6). These increases were driven primarily by higher temperatures, with less influence from stronger winds, greater solar radiation, and a longer growing season.

On the other hand, decreases in seasonal net irrigation requirements were predicted for winter wheat and corn in most regions, depending on the projected direct effects of CO_2 on transpiration. These modeled decreases were generally due to shorter seasons caused by higher temperatures, which accelerates crop life cycles. When crop varieties appropriate to the longer growing season were modeled, irrigation requirements for winter wheat increased. Irrigation water requirements during peak periods increased in almost all cases (Figure 7-7).

Plant canopy (leaf) temperatures were predicted to increase above current baseline values for all crops and sites studied. Projected increases in leaf temperatures may reduce photosynthetic activity and crop yields. (See discussion on direct effects of CO_2 in Chapter 10, Agriculture.)

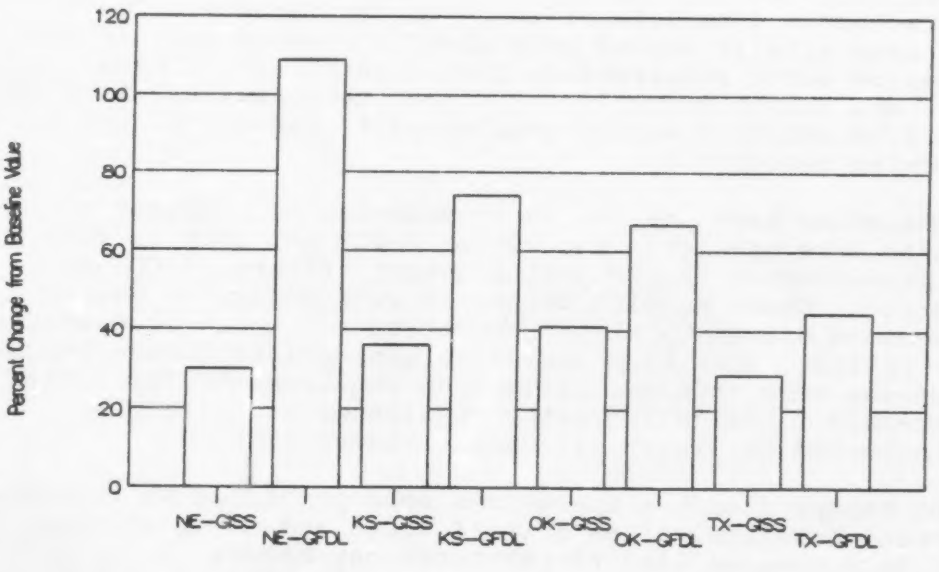

Figure 7-6. Seasonal irrigational requirement for 20% increase in bulk stomatal resistance of alfalfa.

Source: Allen and Gichuki, Volume __.

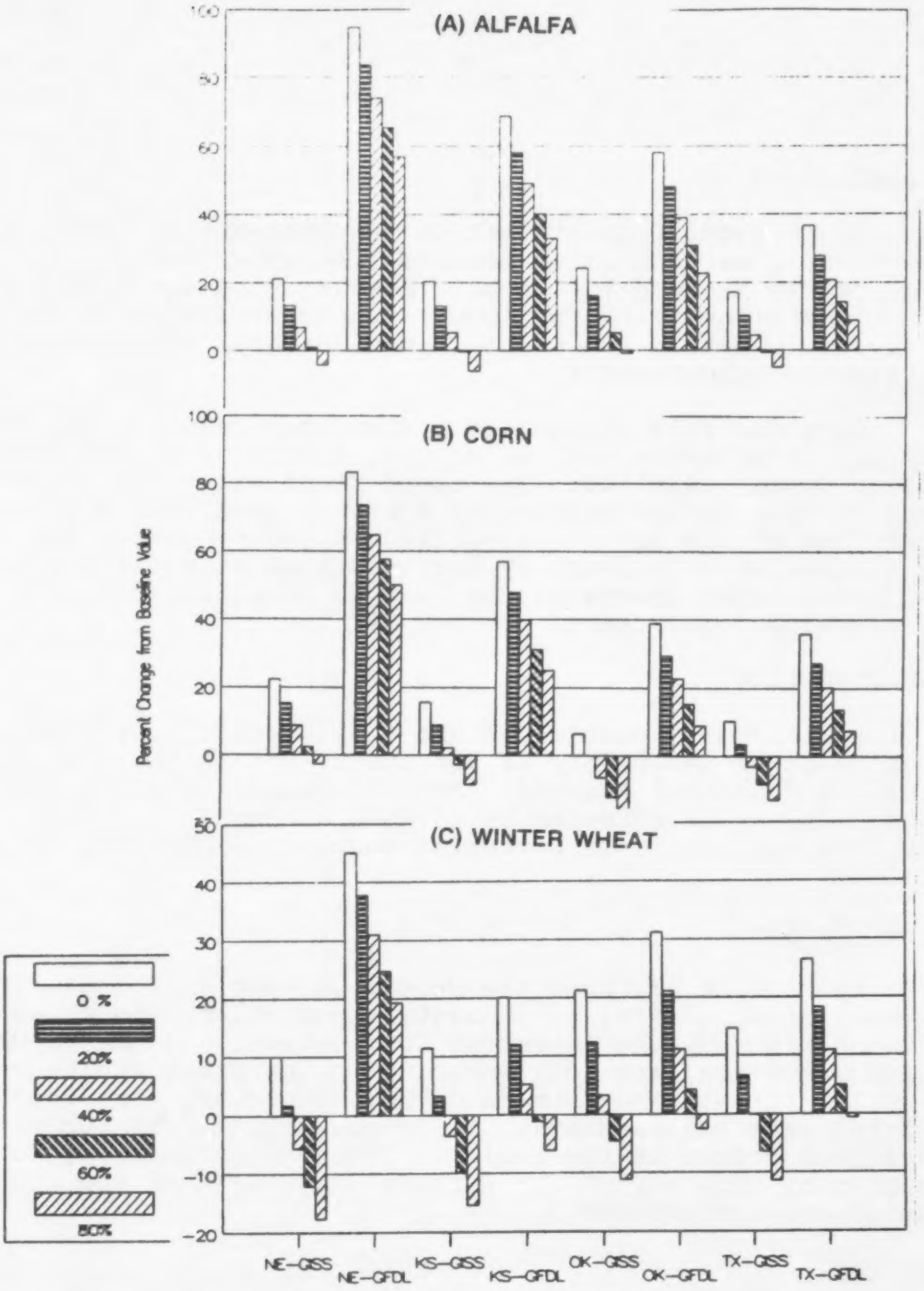

Figure 7-7. Percent change in net peak monthly irrigation requirement from baseline values for alfalfa, corn and winter wheat vs. postulated increases in bulk stomatal diffusion resistance.

Source: Allen and Gichuki, Volume __.

Implications

Any reduction in irrigation requirements for corn and winter wheat would be beneficial because less water and energy would be required to produce the crops. However, the shortened crop durations might allow for longer-season varieties or double-cropping (planting two crops in one season), increasing total irrigation requirements.

Expanded farm irrigation systems may require increased capital investments and larger peak drafts on groundwater systems and on energy supplies. Increased groundwater extraction would pose serious environmental and economic problems, especially where "water mining" is currently a major problem. Any increases in irrigation efficiency by irrigators as an attempt to cope with projected water shortages may lead to increased salinity problems if leaching requirements are not met.

Water Quality

Agricultural pesticides are a high-priority pollution problem in at least half of the States within the U.S. Great Plains and Central Prairie. How the movements of agricultural chemicals may be affected by climate change is essential to a thorough evaluation of potential changes in drinking water quality.

Study Design

Johnson et al. used the Pesticide Root Zone Model (PRZM) to (Carsel et al., 1984) to simulate the partitioning of pesticides between plant uptake, chemical degradation, surface runoff, surface erosion, and soil leaching in the Great Plains under baseline climate and climate change scenarios. The locations modeled were representative of cropping practices for winter wheat and cotton in the region. (See the national agriculture chapter of this report for further discussion of the study's design and limitations.)

Results

As Figure 7-8 shows, in the winter wheat regions of the central Great Plains, surface runoff and surface erosion increase under the GISS scenario, and results are mixed in the GFDL scenario. In the southern Great Plains cotton simulations, the GISS and GFDL scenarios produced increases in surface pesticide losses with runoff and eroded soils.

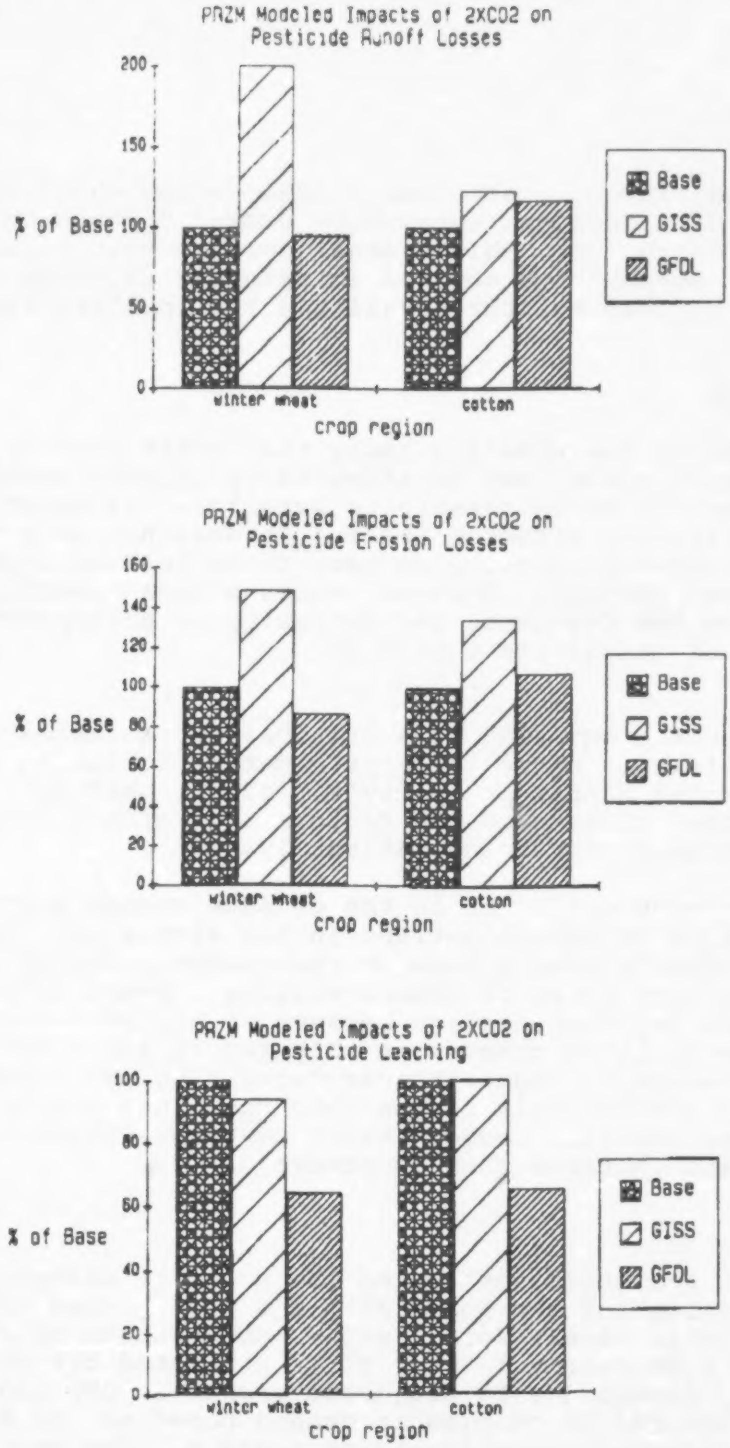

Figure 7-8. Regional summary of surface and subsurface pesticide loss as a percentage of the base climate scenario losses.

Source: Johnson et al., Volume __.

The quantity of pesticides leached below the crop root zone is estimated to decrease everywhere except perhaps on silty soils in the cotton region. This overall decline most likely results from higher evaporative demands in response to temperature increases and less moisture available for infiltration and deep percolation.

Implications

Results of the modeling imply that water quality in the Southern Great Plains may be affected by climate change. Surface water appears to be vulnerable to deterioration under climate change conditions, although the result does not hold for all cases. Groundwater quality appears to be less at risk than surface water quality. However, because these results are highly dependent on the frequency and intensity of precipitation events, directions of change are uncertain.

Livestock

Livestock production is a critical agricultural activity in the Great Plains. Since the approximately 8 million head of beef cattle in Texas represent nearly 40% of all beef cattle in the United States, climate change factors that affect Texas cattle will affect beef production nationally.

The warming predicted in the climate change scenarios may alleviate cold stress conditions in the winter but will most likely exacerbate heat stress in the summer. Warmer summers may necessitate more hours of indoor cooling. Reproductive capabilities may also decline because of higher temperatures. (See the Agriculture chapter in this report for a discussion of livestock issues.) Higher temperatures also may enable tropical diseases to extend their ranges into the Great Plains. High temperatures may also reduce insect pest activities in some locations and increase them in others.

Energy

Linder and Inglis estimated the national changes in demand for electricity for the years 2010 and 2055. (See the Energy chapter of this report for a further description of study's design and methodology.) They first estimated the change in electricity demand due to projected growth in GNP and population, and then factored in changes in demand based on the GISS transient climate change scenarios A and B. The results for the southern and central Great Plains are discussed here.

Table 7-5. Estimated Change in Peak Demand and Annual Energy Requirements Induced by Climate Change (%)

Utility Area	2010				2055	
	GISS A		GISS B		GISS A	
	Ann.	Peak	Ann.	Peak	Ann.	Peak
Kansas/Nebraska	1.7	6.8	1.3	5.2	5.7	22.1
Oklahoma	3.0	7.9	2.8	6.6	11.3	25.3
Texas, east	3.0	7.9	2.8	6.6	11.3	25.3
Texas, south	3.3	10.0	1.7	5.1	10.6	24.6
Texas, west	3.1	8.6	2.4	6.1	11.1	25.1

Source: Linder and Inglis, Volume __.

Results

Estimates of changes in peak demand, capacity requirements, and cumulative and annual costs projected for the climate change scenarios are shown in Table 7-5. New capacity requirements are estimated to increase by 15-28% by 2010 for the climate change scenarios compared to the base case. By 2010, cumulative capital costs induced by climate change may grow by $3.7-6.7 billion, and annual costs may rise by 3-6%.

In 2055, new capacity generating requirements are estimated to increase by 22 to 45 gigawatts or 27-39%. Power generation in the region increased by about 10-14% under the climate change scenarios.

Linder calculated that cumulative capital costs for energy in the region would increase by $20-53 billion with climate change. The estimated changes in annual costs induced by climate change range from $5 to 10 billion -- nearly the same as the $11 billion difference in high and low GNP estimate.

Implications

Increased energy capacity requirements and the need to maintain the reliability of utility systems could place additional stress on the Great Plains. Power plants may take the cooling water they need from rivers or from the already overused Ogallala Aquifer. Fossil fuel plants could add more pollutants to the air.

POLICY IMPLICATIONS

Policymakers may have to respond to a decline of agricultural production in the area, increased demand for water, and poorer water quality. The major issues for policymakers to address include land-use management, water resource management, water quality regulations, and risk management (see Riebsame, Volume _). Regional utility planners and policymakers should also begin to consider climate change as a factor -- along with other uncertainties -- affecting their resource availability analyses and planning decisions.

Land-Use Management

State land managers should analyze how their missions and holdings may be affected by climate change and should develop flexible strategies to deal with potential impacts. Federal agencies, such as the Department of Agriculture, the Forest

Service, the Fish and Wildlife Service, and the Department of Interior, should work with State agriculture, forest, and park agencies on such plans.

Agriculture and other uses may shift across several States. This adjustment process can be made more efficient and less disruptive if individual jurisdictions, such as municipalities, States, and federal regions respond in a coordinated manner. Decisions made by managers of agriculture will affect decisions on forests, wildlife, water resources, and other areas. Decisionmakers should work together on developing sound and flexible anticipatory strategies, and new institutional arrangements may be needed.

Some programs already in place can help to lessen the negative effects of climate change on the Great Plains. Federal legislation such as the "Sod-Buster Bill" and the related "Swamp-Buster Bill," and the Conservation Reserve Program, are examples of new policies designed to reduce the use of marginal lands for agriculture. These laws have the basic goals of protecting the most erodible farmlands by removing them from crop production and of using conservation as a tool for reducing overproduction. These policies are prudent now for reducing runoff and erosion, and may become even more important for protecting water quality in light of climate change. Protection of marginal lands may have to be weighed against the need for greater crop production if climate change lowers yields.

Water Resource Management

With climate change, parts of the Great Plains are likely to suffer increasing aridity. Farmers may demand more water for irrigation, although groundwater sources are already taxed. Competition for water resources between agricultural and nonagricultural demands may be exacerbated. Managers need to factor these potential effects of climate change into their decisions on irrigation, drainage, and water transfer systems and as they formulate supply allocation rules, reservoir operating criteria, safety protocols, and plans for long-term water development. Water conservation techniques, water reallocation between competing uses, water transfers and markets, and land-use adjustments must be evaluated for their ability to absorb the effects of future climate change. Primary consideration should be given to environmentally sound programs for managing water resources.

Water Quality Regulations

Decisionmakers should consider the potential effects of climate change on water quality and the use of pesticides. They should examine alternative pest control strategies, such as Integrated Pest Management, which uses such techniques as biological control, genetic resistance, and innovative cropping systems to reduce pesticide applications.

Risk Management

Several government, semi-private and private institutions have a large financial stake in Great Plains agriculture through land credit, commodity and equipment loans, and insurance. Additionally, the federal government provides disaster relief for climate extremes affecting regional agriculture. Climate warming poses a potential long-term risk to the financial institutions supporting agriculture, the resources available for emergency relief, and to individual farmers. This consideration should be carefully assessed and the risk monitored as climate changes.

REFERENCES

Carsel, R.F., C.N. Smith, L.A. Mulkey, J.D. Dean, and P. Jowise. 1984. Users Manual for Pesticide Root Zone Model: PRZM. USEPA/ERL Report EPA-600-3-84-109. Washington, DC: U.S. Government Printing Office.

Glantz, M.H., and Ausubel, J.H. 1984. The Ogallala Aquifer and carbon dioxide: Comparison and convergence. Environ. Conser. 11(2):123-31.

High Plains Associates. 1982. Six-State High Plains-Ogallala Aquifer Regional Resources Study. Austin, Texas.

Hurt, R.D. 1981. The Dust Bowl. Chicago: Nelson-Hall.

Jones, C.A., and J.R. Kiniry. 1986. CERES-Maize: A Simulation Model of Maize Growth and Development. College Station, TX: Texas A&M Press.

Liverman, D.M., W.H. Terjung, J.T. Hayes, and L.O. Mearns. 1986. Climatic change and grain corn yields in the North American Great Plains. Climatic Change 9:327-347.

Lockeretz, W. 1978. The lessons of the Dust Bowl. American Scientist 66:560-569.

Monteith, J.L. 1965. Radiation and crops. Experimental Agriculture Review 1(4):241-251.

New York Times. August 12, 1988. Drought cutting U.S. grain crop 31% this year. By K. Schneider. p. A1.

Riebsame, W.E. 1983. Managing agricultural drought: The Great Plains experience. In: Platt, R., and G. Macinko, eds. Beyond the Urban Fringe: Land Use Issues in Non-Metropolitan America. Minneapolis: University of Minnesota Press, pp. 257-270.

Riebsame, W.E. 1987. Human Transformation of the United States Great Plains: Patterns and Causes. Proc. Symp on The Earth as Transformed by Human Action, Clark University.

Ritchie, J.T., and S. Otter. 1985. Description and performance of CERES-Wheat: A user-oriented wheat yield model. In: Willis, W.O., ed. ARS Wheat Yield Project. USDA-ARS. ARS - 38. pp. 159-175.

Robertson, T., V.W. Benson, J.R. Williams, C.A. Jones, and J.R. Kiniry. 1987. Impacts of climate change on yields and erosion for selected crops in the southern United States. In: Meo, M., ed. Proc. Symp. on Climate Change in the Southern U.S.: Impacts and Present Policy Issues, Science and Public Prog., Univ. of Oklahoma, Norman, OK.

Rosenzweig, C. 1985. Potential CO_2-induced climate effects on North American wheat-producing regions. Climatic Change 7:367-389.

Rosenzweig, C. 1987. Climate change impact on wheat: The case study of the High Plains. In: Meo, M., ed., Proc. Symp. on Climate Change in the Southern U.S.: Impacts and Present Policy Issues, Science and Public Prog., Univ. of Oklahoma, Norman, OK.

Terjung, W.H., D.M. Liverman, J.T. Hayes et al. 1984. Climatic change and water requirements for grain corn in the North American Great Plains. Climatic Change 6:193-220.

Warrick, R.A. 1984. The possible impacts on wheat production of a recurrence of the 1930s drought in the U.S. Great Plains. Climatic Change 6:5-26.

Warrick, R.A., and M.J. Bowden. 1981. The changing impacts of drought in the Great Plains. In: Lawson, M.P., and M.E. Baker, eds. The Great Plains: Perspectives and Prospects. Lincoln: University of Nebraska Press, pp. 111-137.

Worster, D. 1979. Dust Bowl: The Southern Great Plains in the 1930s. New York: Oxford University Press.